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# Distribution and origin of elongate sandstone concretions, Bullion Creek and slope formations (Paleocene), Adams County, North Dakota

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# DISTRIBUTION AND ORIGIN OF ELONGATE SANDSTONE CONCRETIONS, BULLION CREEK AND SLOPE FORMATIONS (PALEOCENE), ADAMS COUNTY, NORTH DAKOTA

by
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This thesis submitted by Michael W. Parsons in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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This thesis meets the standards for appearance and conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

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TABLE OF CONTENTS

## ILLUSTRATIONS

Plate

LIST OF TABLES

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ABSTRACT

Rectilinear patterns in sandstone are visible on aerial photographs of Adams County, North Dakota. These patterns result from the differential erosion of elongate, calcareous, sandstone concretions that have formed in fluvial channel sand units.

The distribution and orientation of the elongate concretions were mapped from aerial photographs. The concretions have a strongly east-west orientation. Averages of paleocurrent measurements of the associated sand and sandstone are also easterly.

The elongate concretions occur slightly above and below the Rhame bed (a white marker zone at the top of the Slope Formation), in sand units at the base of the Bullion Creek Formation and at the top of the Slope Formation. The concretions are commonly one to two metres thick, several metres wide, and at least ten metres long. Their longest dimension is parallel to bedding in the sand. Bedding commonly continues from the sand into the sandstone concretion. The concretions occur along distinct horizons that terminate laterally and recur vertically, ruling out their use as stratigraphic markers. In some areas, individual elongate concretions are laterally connected, forming a tabular bed with aligned "pinchings" and "swellings." This indicates an advanced stage of concretion growth. The concretions do not contain a recognizable, macroscopic, organic nucleus.

No compositional differences were found between the concretions and the enclosing sand, but the sand has a significantly lower porosity.

This suggests the sand has undergone more compaction, and that the concretions formed before the sediment reached its presently compacted state. In light of this evidence, a late diagenetic age seems most likely.

At some time in the past, calcium- and carbonate-enriched groundwater probably flowed eastward through Adams County, following the positions of buried paleochannels. Calcite precipitation occurred in discrete centers when the pH rose above 7.8. The elongate form of the concretions is a result of preferred growth parallel to the direction of groundwater flow. Therefore, the concretions can be used as directional indicators of paleogroundwater flow.

# INTRODUCTION

## Purpose of Study

Resistant, butte- and ridge-forming sandstone occurs in southern Adams County. The sandstone is composed of linear, elongate forms in parallel or subparallel arrangement, apparent on aerial photographs (Figure 1) and in outcrop (Figure 2). The sandstone bodies have ellipsoidal outlines, with their longest axes parallel to bedding planes. They are encased in and sharply separated from the enclosing, unlithified sand. The sandstone bodies are cemented with calcium carbonate, and are more resistant to erosion than the surrounding sand. Bedding is continuous from the enclosing sand into the sandstone, indicating the elongate forms are post-depositional in origin. Based on the above characteristics, I believe the term "concretion" most accurately describes these sandstone forms. It will be used throughout the remainder of the paper when referring to the bodies.

The purposes of this study are to document occurrences of the elongate sandstone concretions, describe their appearance in outcrop, determine their stratigraphic position(s), and suggest a mode (or modes) of origin.

## Study Area

The study area is the southern half of Adams County, North Dakota and, to a small extent, the very north of Perkins County,

Fig. 1. Aerial photograph near Reeder, North Dakota. Arrows point out rectilinear patterns which are elongate, sandstone concretions in Bullion Creek Formation. The number 2 indicates location of elongate concretion in Figure 2. Location is T.130N., R.98W., sec. 9, 10, 15, 16.

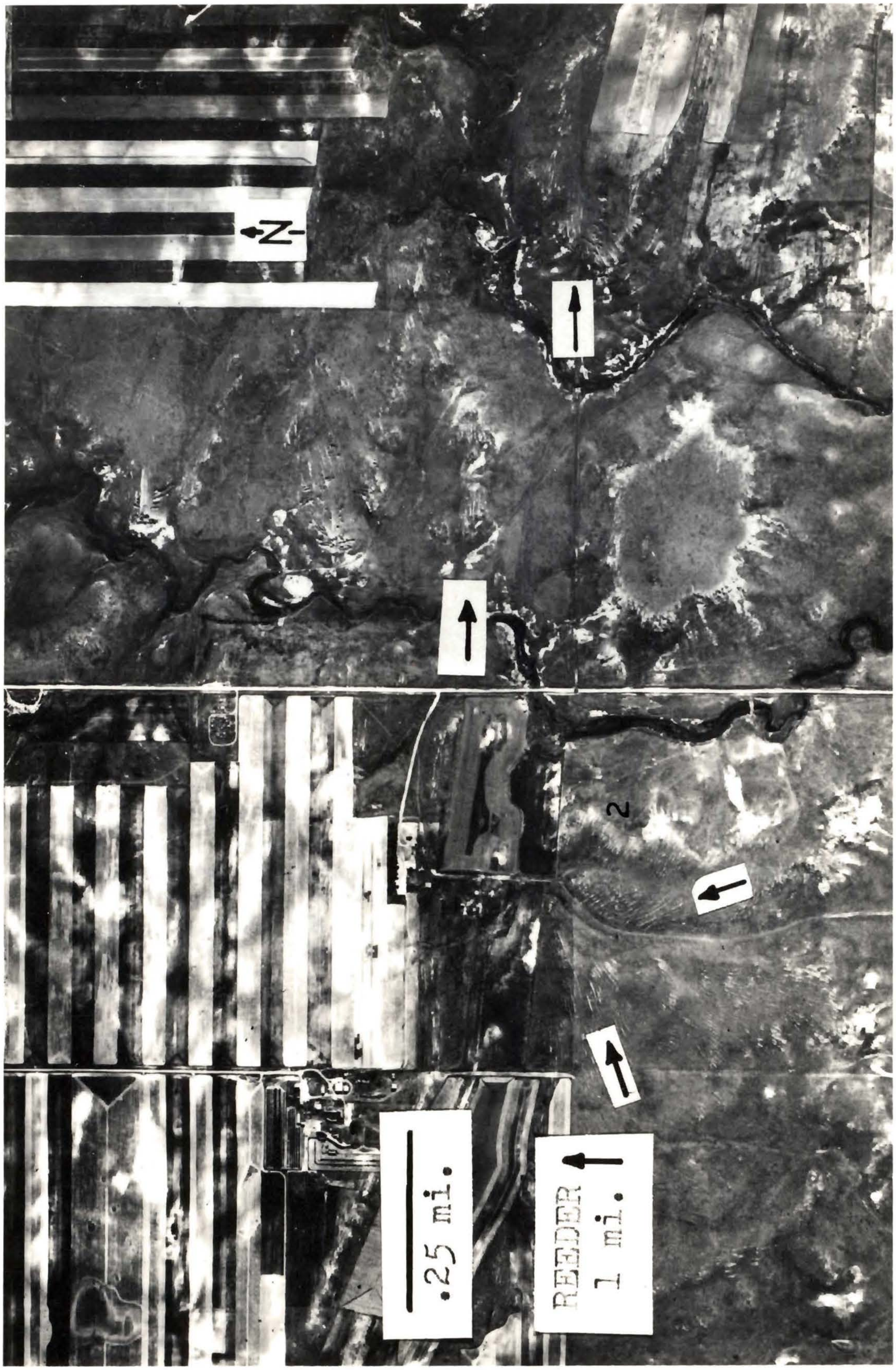

N
2
.25 mi.
REEDER
1 mi.

Fig. 2. Elongate, calcareous sandstone concretion, encased in sand in Bullion Creek Formation. Concretion is located in Figure 1 by the number 2. Note horizontal jointing in concretion which parallels bedding. View is northwest. Location is T. 130 N., R. 98 W., sec. 16, NE¼, NE¼, east side of low hill, 1/2 mile south of Rose Hill Cemetery. Pick is 0.9 m long.

South Dakota (Figure 3). The study area was chosen from aerial photographs as the area of highest density of concretion-bearing sandstone outcrops.

## Geologic Setting

Adams County lies within the unglaciated Missouri Plateau section of the Great Plains Province. The area is characterized by generally low relief with gentle slopes interrupted by low buttes or ridges. The buttes and ridges are held up by sandstone (the subject of this study), "scoria" (sediment altered by the burning of lignite), or silcrete. Adams County is drained primarily by Cedar and Duck Creeks, which flow to the southeast.

Formations exposed at the surface in Adams County were deposited during Paleocene time on the southern flank of the Williston Basin. Presently, they have a very slight dip to the north-northwest (toward the basin center).

The Paleocene formations exposed in the study area (Figure 4) form a sequence of fluvial channel and flood-basin deposits consisting of sand, silt, clay, and lignite. Drainage during this time was generally eastward, reflecting the presence of western uplands formed during the Laramide orogeny (Royse 1967). Continental deposition during the Paleocene Epoch was interrupted episodically by paralic deposition of the marine Cannonball Formation, which is exposed in the eastern portions of the county.

The exposures of sand and sandstone in Adams County have previously been referred to the "Tongue River" Formation. On the basis of discrepancies in the definition of the upper and lower Tongue River

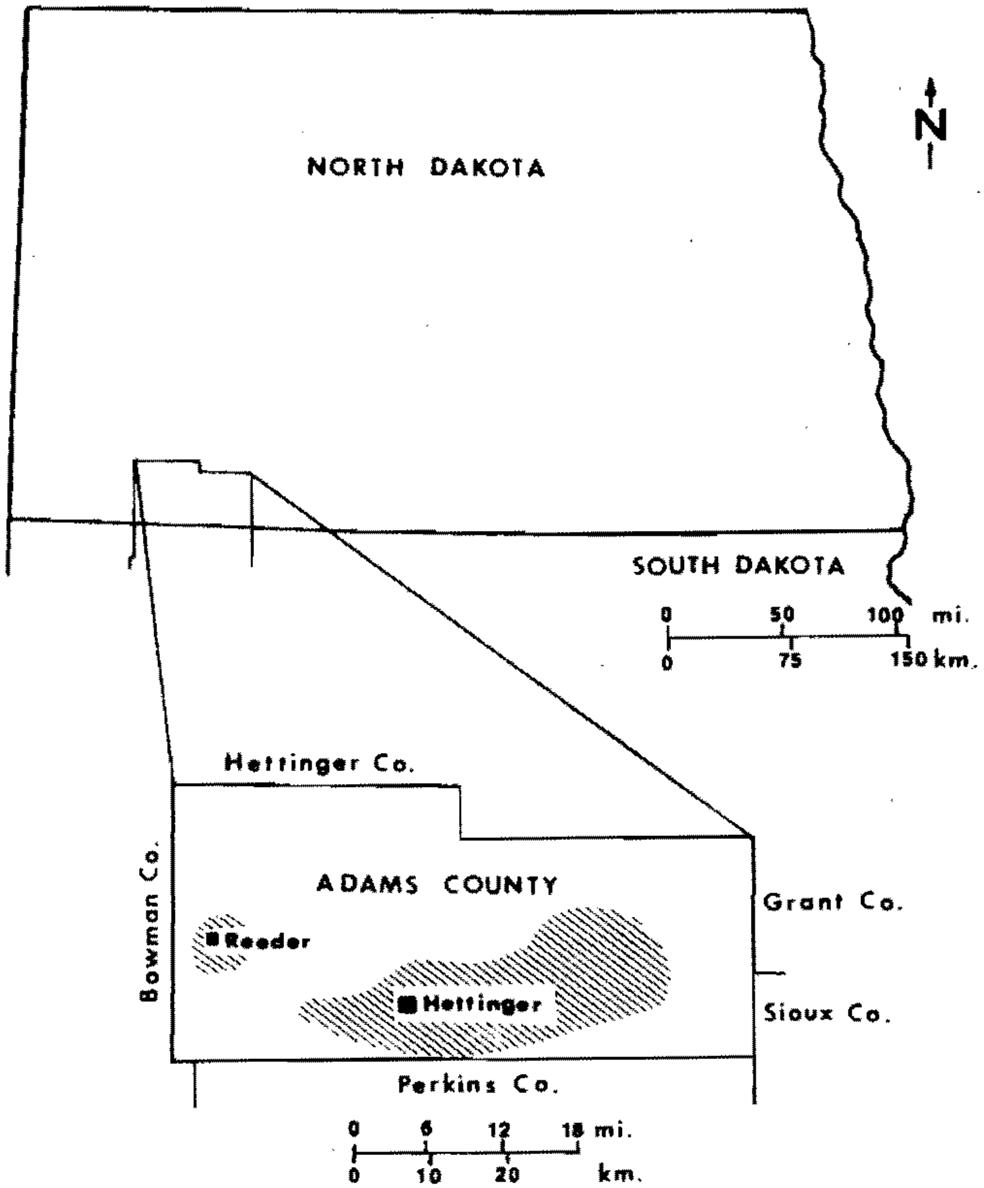



Fig. 3. Location map of Adams County, North Dakota. Ruled portion is study area.

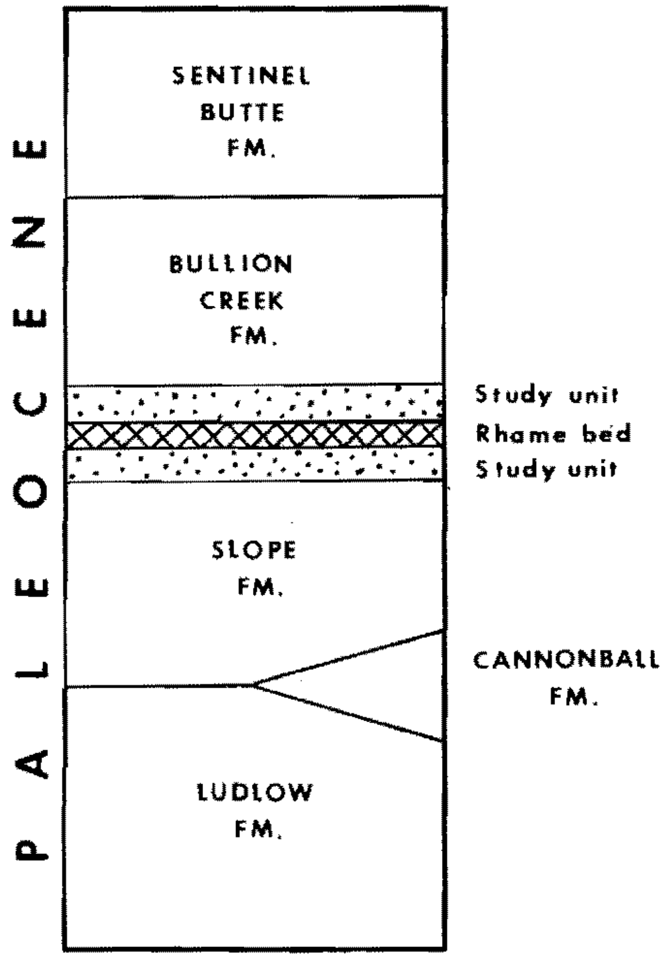



Fig. 4. Paleocene rock units exposed in Adams County. Rhame bed marks top of Slope Formation. Thicknesses of units are not to scale.

contacts in South Dakota, Montana, and southwestern North Dakota, Clayton et al. (1977) renamed the Tongue River Formation and part of the underlying Ludlow Formation as the Bullion Creek (above) and Slope (below) Formations. The contact between the two formations is regarded as the top of a white-weathering unit, the Rhame bed (Figure 5).

The Bullion Creek Formation consists of alternating beds of clay, silt, sand, and lignite. Clayton et al. (1977) reported that the bottom portion of the formation is especially sandy. This probably includes some of the sand and sandstones in Adams County. Most of the formation is light yellow in outcrop, which distinguishes it from the underlying Slope Formation. Its thickness is approximately 90 metres (300 feet) in this area, based on subsurface drilling information (Carlson 1979).

The Slope Formation is lithologically similar to the Bullion Creek Formation, but is distinguished by its drab, brownish color and by the presence of the Rhame bed at its top. Clayton et al. (1977) showed a thick sand bed at the top of the type section of the Slope Formation. Some of the sandstone concretions of Adams County may belong to this uppermost sand unit. The Slope Formation is poorly exposed in the study area and has a thickness of 18 to 24 metres (60 to 80 feet) (Carlson 1979). This unit overlies the marine Cannonball Formation in the eastern portion of the county, and the nonmarine Ludlow Formation in the west (Carlson 1979).

The Rhame bed. The Rhame bed is a white-weathering unit, composed of several metres of white to light gray sand, silt, or clay capped by several decimetres of resistant, white silcrete (Figure 6).

Fig. 5. Cross section of Bullion Creek and Slope Formations in Adams County, North Dakota. Cross section shows variability in stratigraphic position of elongate sandstone concretions. Size of elongate concretions is not to scale. Numbers at top of lithologic columns refer to measured sections in appendix D.

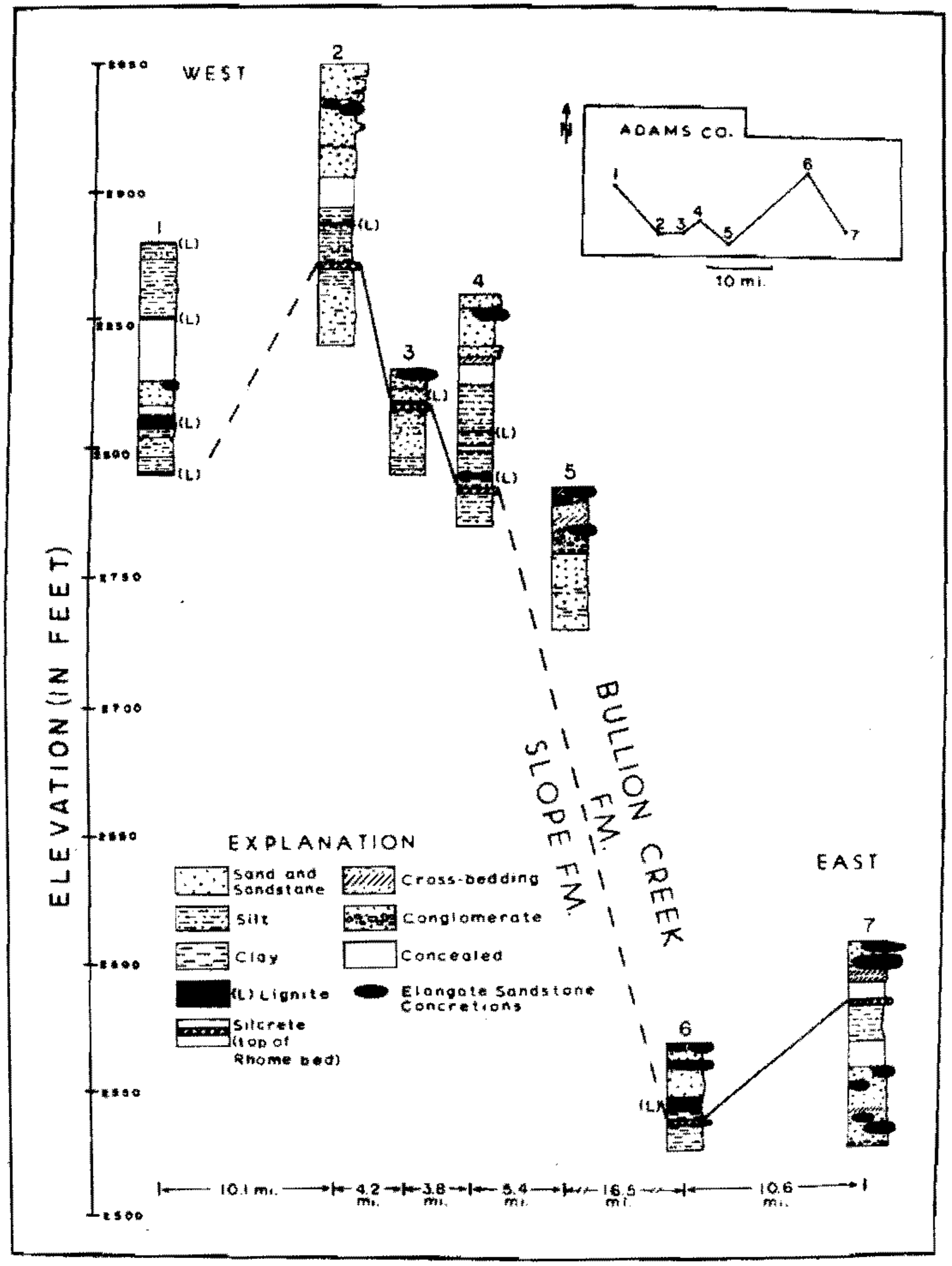

WEST
EAST
ELEVATION (IN FEET)
ADAMS CO.
10 mi.
BULLION CREEK FM.
SLOPE FM.
EXPLANATION
Sand and Sandstone
Silt
Clay
(L) Lignite
Silcrete (top of Rhome bed)
Cross-bedding
Conglomerate
Concealed
Elongate Sandstone Concretions
10.1 mi.
4.2 mi.
3.8 mi.
5.4 mi.
16.5 mi.
10.6 mi.

Fig. 6. Contact between Bullion Creek and Slope Formations. Pick handle (0.9 m) rests on top of white, resistant silcrete of Rhame bed at top of Slope Formation. Note variable cementation of Bullion Creek sandstone. Location is T. 129 N., R. 96 W., sec. 17, SE¼, NE¼; site of measured section 3 (appendix D).

In Adams County, the bed crops out on the tops of low buttes, at the present ground surface in large, level areas, and in steep slopes. Although laterally discontinuous, it is a mappable unit (Wehrfritz 1978). In Adams County, it is the best criterion for distinguishing Bullion Creek from Slope outcrops. The Rhame bed occurs in close association with the concretion-bearing sands, at both slightly higher and lower elevations. This indicates that the elongate sandstone concretions lie within the lower Bullion Creek and upper Slope Formations.

## Previous Work

Adams County. Because the use of "Bullion Creek" and "Slope" for "Tongue River" is recent, much of the literature on the geology of Adams County uses the older term. To avoid confusion, I have used the current nomenclature when referring to previous work on these strata. The reader should recognize this minor amendment.

The earliest geologic work in this area (Lloyd 1914) was reconnaissance mapping to determine the extent of lignite reserves. Lloyd (1914) gave a systematic description of the geology of each township. In the southern townships, he noted buttes and ridges capped by resistant sandstone up to 40 feet thick.

Carlson (1979) mapped the geology of Adams County. In the accompanying text, he noted sandstone-capped ridges and knobs along drainage divides, and the varying cementation of the sandstone, but did not deal with geometry or origin.

The most detailed work on the resistant sandstones has been by Jacob (1973, 1976). He used the term "elongate sandstone concretions" in describing the features. Based on similarities between cross-bedding azimuths and direction of elongation of the associated sandstone concretions, he suggested that the regional distribution of the elongate concretions can be used to predict the position and orientation of paleochannels in the Bullion Creek Formation. In extending his study to the Medora, North Dakota area, where exposures of Bullion Creek channel sands are more complete, he found that this relationship between paleocurrents, channel sand position, and direction of concretion elongation is maintained, although fewer concretions are exposed than in Adams County.

Elongate sandstone concretions. In North Dakota, sandstone bodies cemented with calcite into an elongate form and encased in sand, have been termed "log concretions" and have been reported from the "Laramie" (equivalent to portions of the Hell Creek, Ludlow, and Cannonball Formations) (Todd 1903), Hell Creek (Frye 1967; Groenewold 1971), and Ludlow Formations (Frye 1967). With regard to lithology, size, geometry, and relationship with surrounding sediment, these "log concretions" closely resemble the linear, elongate sandstone concretions studied in this report.

In studying "log-like" concretions of the "Laramie" Formation, Todd (1903) believed the isolated centers of calcite cementation were controlled by the presence of organic matter, possibly lying on ancient beaches in interdune areas. Therefore, he concluded the regional distribution of the "log-like" concretions might parallel ancient shorelines.

Frye (1967) and Groenewold (1971) analyzed the Hell Creek sandstone concretions petrographically. They suggested that the concretions originated by precipitation of calcium carbonate from ancient groundwater that migrated parallel to buried channel sands of the Hell Creek Formation. They felt that because of greater permeability in these directions, the concretions can be used to predict paleodrainage patterns. However, neither worker presented any paleocurrent evidence to substantiate this conclusion.

Stevenson (1954) studied concretionary bodies in sandstone of the Hell Creek, Ludlow, Cannonball, and Tongue River Formations of northwestern South Dakota. He noted "log-like" concretions in the Hell Creek and Tongue River Formations. Stevenson believed these concretions actually represent "incomplete diagenetic cementation" and, therefore, proposed they be termed "cementations" (Stevenson 1954, p. 50).

Meschter (1958) reported concretions similar to those of Adams County from the Wasatch Formation (Eocene) in the Powder River Basin of Wyoming. He termed these features "tubular concretions" (p. 5) and suggested that their orientations were controlled by paths of migrating groundwater. Their northerly trend may be a result of ancient groundwater flowing away from Precambrian basement highs to the south.

## Methods

Preliminary work consisted of inspecting aerial photographs of Adams County for occurrences of elongate concretions. The number, location, and orientation of the concretions were recorded to the nearest quarter-section on a base map of the county. Plate 1 represents all elongate sandstone concretions visible on aerial photographs in Adams County. The orientation of each line segment represents the orientation of a concretion or group of concretions. The number associated with each line segment is the number of elongate concretions having the same orientation in a given square-mile section. Adjacent concretions whose orientation differed by less than three degrees were usually lumped together. No attempt was made to represent the concretions according to relative size, because of difficulties of scale. Appendix A (table 2) lists the location, orientation, and frequency of elongate concretions represented on Plate 1.

To simplify the data of Plate 1 and to better show the average orientation of the concretions, fifty random numbers were chosen, using the random number generator on a Texas Instruments programmable calculator (TI-59). Each random number corresponded to a section on Plate 1 that contained at least five elongate concretions. Generally, sections with fewer than five line segments were those with indistinct concretions on aerial photographs. I felt that sampling for purposes of averaging should be done in the areas of highest frequency where identification of the concretions was the soundest. The vector mean $(\bar{\alpha})$ and vector strength $(\bar{a})$ were then calculated for each section (table 1), according to the formulas of Pincus (1956). The vector mean was used as a measure of average orientation because the data are circularly oriented. The arithmetic mean of several widely different compass readings would not give the true average, especially if values occurred on either side of zero degrees (due north). For example, the arithmetic mean of 350 degrees and 10 degrees is 180 degrees, but the vector mean is zero degrees. In this case, the arithmetic mean does not reflect the northerly aspect of the two vectors. The vector strength $(\bar{a})$ is a measure of data dispersion. The value of $\bar{a}$ can vary between zero and 1.00. A value of zero indicates complete nonuniformity of the data, and a value of 1.00 indicates complete uniformity. The calculation of $\bar{\alpha}$ and $\bar{a}$ was performed by computer, using a program written by Susan Daut, Iowa Geological Survey, and adapted by David B. Johnson, Department of Geology, University of North Dakota. The results are listed in table 1 and shown graphically in Figure 7.

Field work consisted of the following: measuring sections to determine the stratigraphic position(s) of the concretion-bearing sands; describing the geometry, orientation, and internal characteristics of the concretions and their relationship with the surrounding sediment; measuring orientations of cross-bed sets in the sandstone to construct paleocurrent rose diagrams; and collecting samples of the sandstone and enclosing sand for petrographic analysis.

Paleocurrent data were recorded at all outcrops where enough cross-bedding readings could be collected to define a mode (usually at least ten readings). All azimuths for one square-mile section were grouped together, provided modes for individual outcrops were similar. Large-scale cross-bed sets (thickness greater than 4 cm) were used for directional data whenever possible, but azimuths of some small-scale sets were also included, if their orientations could be determined accurately. The axis of a cross-bed set was used as an orientation indicator. In this way, the apparent dip of the cross-bed set did not influence measurements. The azimuths, recorded to the nearest degree, are listed by location in appendix B (table 3). Azimuths for each section were then plotted on a circular diagram divided into 36 ten-degree classes (Figure 7). The vector mean $(\bar{\alpha})$ and vector strength $(\bar{a})$ were calculated using the same formulas and

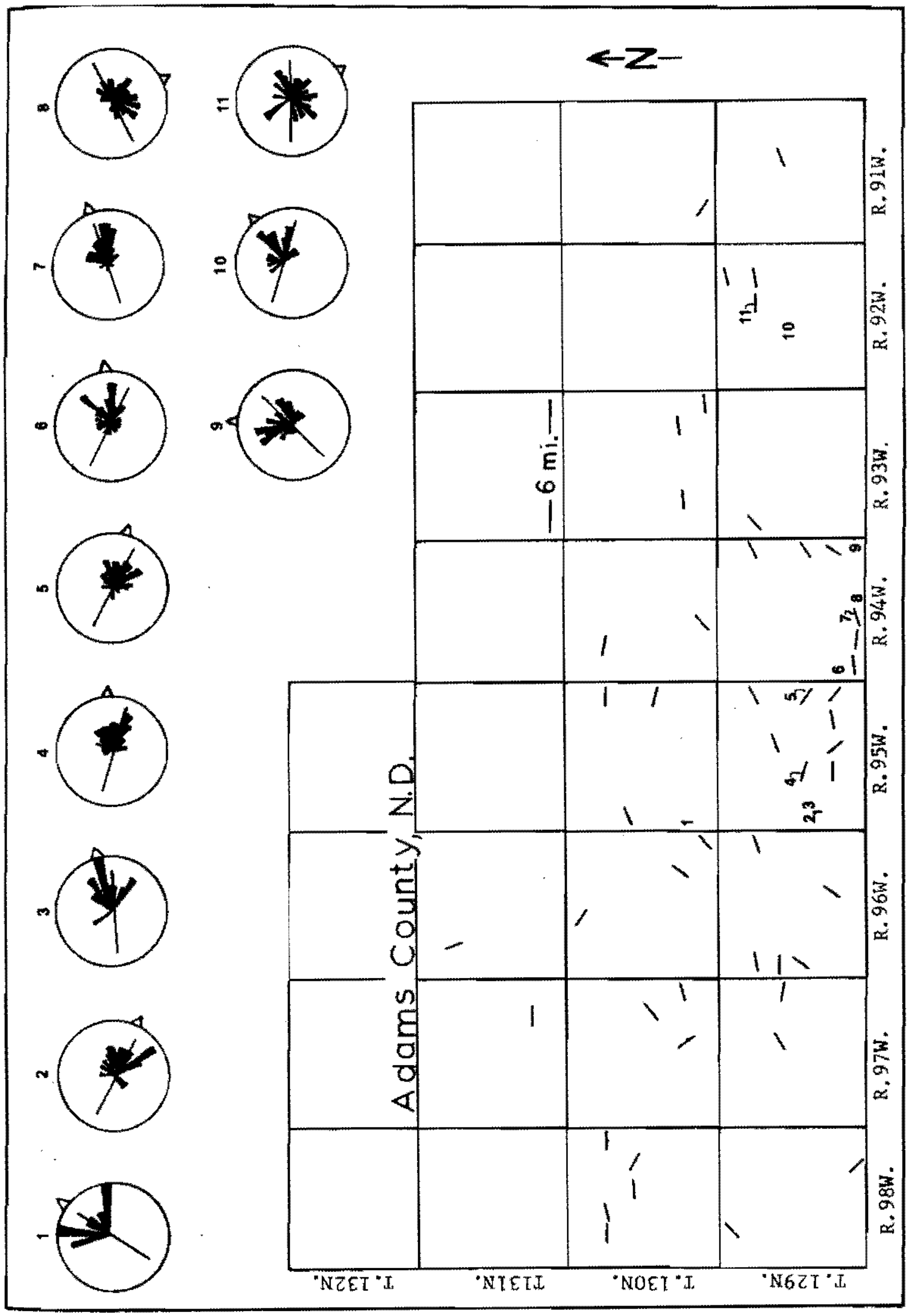
TABLE 1

AVERAGE ELONGATE CONCRETION ORIENTATIONS OF FIFTY RANDOMLY CHOSEN SQUARE-MILE SECTIONS

| Location | | | | | | Location | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Twn-ship | Rnge | Sec-tion | No. of rdngs | $\bar{\alpha}$ | $\bar{a}$ | Twn-ship | Rnge | tion | No. of rdngs | $\bar{\alpha}$ | $\bar{a}$ |
| 129N | 91W | 15 | 28 | 69 | 0.95 | 129N | 97W | 15 | 5 | 60 | 1.00 |
| 129N | 92W | 2 | 20 | 76 | 0.99 | 129N | 98W | 5 | 16 | 49 | 1.00 |
| 129N | 92W | 10 | 33 | 90 | 1.00 | 129N | 98W | 35 | 7 | 138 | 1.00 |
| 129N | 92W | 11 | 78 | 80 | 1.00 | 130N | 91W | 32 | 5 | 123 | 1.00 |
| 129N | 93W | 7 | 7 | 46 | 1.00 | 130N | 93W | 26 | 5 | 83 | 1.00 |
| 129N | 94W | 12 | 7 | 60 | 0.98 | 130N | 93W | 29 | 14 | 86 | 0.99 |
| 129N | 94W | 24 | 38 | 58 | 1.00 | 130N | 93W | 36 | 13 | 83 | 1.00 |
| 129N | 94W | 25 | 13 | 36 | 0.98 | 130N | 94W | 8 | 34 | 101 | 0.98 |
| 129N | 94W | 31 | 10 | 83 | 0.99 | 130N | 94W | 33 | 15 | 45 | 1.00 |
| 129N | 94W | 32 | 5 | 96 | 1.00 | 130N | 95W | 12 | 30 | 91 | 1.00 |
| 129N | 94W | 33 | 70 | 73 | 1.00 | 130N | 95W | 18 | 34 | 68 | 0.96 |
| 129N | 95W | 12 | 11 | 62 | 1.00 | 130N | 95W | 24 | 13 | 104 | 0.98 |
| 129N | 95W | 15 | 8 | 73 | 1.00 | 130N | 96W | 4 | 6 | 122 | 0.96 |
| 129N | 95W | 21 | 68 | 106 | 0.97 | 130N | 96W | 26 | 8 | 36 | 0.99 |
| 129N | 95W | 24 | 41 | 122 | 0.99 | 130N | 96W | 36 | 72 | 46 | 0.85 |
| 129N | 95W | 25 | 15 | 129 | 1.00 | 130N | 97W | 23 | 8 | 52 | 1.00 |
| 129N | 95W | 26 | 56 | 79 | 0.97 | 130N | 97W | 25 | 9 | 75 | 1.00 |
| 129N | 95W | 27 | 18 | 139 | 0.95 | 130N | 97W | 27 | 11 | 146 | 1.00 |
| 129N | 95W | 28 | 13 | 92 | 0.99 | 130N | 98W | 8 | 37 | 90 | 0.95 |
| 129N | 96W | 7 | 32 | 76 | 1.00 | 130N | 98W | 9 | 9 | 73 | 1.00 |
| 129N | 96W | 12 | 16 | 70 | 0.99 | 130N | 98W | 12 | 17 | 90 | 1.00 |
| 129N | 96W | 18 | 14 | 90 | 1.00 | 130N | 98W | 14 | 35 | 116 | 0.92 |
| 129N | 96W | 19 | 22 | 39 | 0.98 | 130N | 98W | 15 | 30 | 86 | 0.95 |
| 129N | 96W | 27 | 23 | 32 | 0.98 | 131N | 96W | 8 | 9 | 159 | 1.00 |
| 129N | 97W | 13 | 5 | 97 | 1.00 | 131N | 97W | 26 | 12 | 91 | 0.98 |

NOTE: Only the east portion of east-west azimuths was listed for convenience. The grand vector mean of the $\bar{\alpha}$ values is 82 degrees.

Fig. 7. Map of Adams County showing elongate concretion orientations for 50 square-mile sections chosen at random. Numbers (1-11) on county map correspond to paleocurrent rose diagrams above. Each number is located in the center of the square-mile section from which paleocurrent readings were taken. Line in each rose diagram is the average elongate concretion orientation for that square-mile section. Arrow on outside of perimeter of each rose diagram is the mean azimuth of the paleocurrents. Data on location and orientation of elongate concretions is given in table 1. Data on paleocurrent rose diagrams is given in appendix B (table 3).


Adams County, N.D.
6 mi.
N
R.98W.
R.97W.
R.96W.
R.95W.
R.94W.
R.93W.
R.92W.
R.91W.
T.132N.
T131N.
T.130N.
T.129N.
1
2
3
4
5
6
7
8
9
10
11

computer program referred to earlier. This information is reported in appendix B (table 3).

Three pairs of sand and sandstone samples were collected during the field work. Samples of an elongate sandstone concretion and the adjacent, unlithified, friable sand were collected in order to analyze the detrital composition and to search for possible porosity differences. The location and elevation of each sample is listed in appendix C (table 4).

In the laboratory, the friable sand samples were immersed in a mixture of epoxy resin and hardener and evacuated in a bell jar. This procedure forced the epoxy into the porous sample, producing an artificial cement and preserving the original grain fabric. The samples were thin-sectioned, stained with alizarine red S to highlight calcite cement, and point-counted. Two hundred points of detrital grains, voids, and cement were counted on each slide. The amount of voids and cement were combined to give an estimate of porosity in the sand and sandstone (appendix C, table 7). Two assumptions were made: (1) that all calcite cement was void-filling, and did not form by recrystallization; and (2) that grain shoving by expansive growth of calcite was minimal. The quantities of each detrital grain type, excluding the quantities of voids and cement, were normalized to 100 per cent to determine whether a compositional difference existed between the sand and the concretionary sandstone. These data are shown in appendix C, (table 5).

A second point-count was made of platy grains (mica grains and clay particles) to indicate the degree of compaction in the

the sample. Approximately 20 platy grains were counted in each thin section, classified as either deformed or undeformed, and normalized to 100 per cent. These data are shown in appendix C (table 8).

## RESULTS

### Regional Distribution of Elongate Concretions

The regional distribution of the elongate concretions is shown on Plate 1. The features shown represent only those concretions large enough to be visible on aerial photographs. Smaller ones also exist. The concretions crop out mainly in the southern half of the county. Three clustered areas of exposed concretions are apparent: (1) in the western part of the county near Reeder; (2) in the south-central part of the county near Hettinger and Haynes; and (3) in the eastern portion of the county, north of Lemmon, South Dakota.

The dominant orientation of the elongate sandstone concretions is east-west. This is shown by the $\bar{\alpha}$ (vector mean) values and corresponding $\bar{a}$ (vector strength) values (table 1). The grand vector mean (vector mean of the 50 values in table 1) is 82 degrees; that is, nearly east-west. All of the $\bar{a}$ values (table 1) are nearly 1.00. This indicates a very high uniformity of concretion orientations.

### Description of Elongate Concretions in Outcrop

Topographic occurrences. Since they are more resistant than the enclosing sand, the concretions tend to occur as cap rocks above a thicker sand sequence. However, the range of topographic occurrences varies, depending on the degree of erosion. In some areas, the concretions are barely visible in outcrop as rectilinear patterns flush with ground level (Figure 8).

Fig. 8. Rectilinear pavements in Bullion Creek Formation near Reeder, North Dakota. This is actually surficial expressions of elongate sandstone concretions. Location is T. 130 N., R. 98 W., sec. 16, NE¼, NE¼, west side of low hill, about 1/2 mile southwest of Rose Hill Cemetery. Pick (arrow) is 0.9 m long.

In many cases, the concretions form distinct horizons that recur vertically and terminate laterally (Figures 5 and 9). Because of this, they cannot be used for stratigraphic markers.

Enclosing sand units. The elongate concretions are encased in less-resistant, yellow sand units. The sand units have variable thicknesses, fill scours into underlying sediments, and recur vertically. The geometry of the sand units cannot be determined accurately because the uncemented character causes the sand to be eroded away, leaving the sandstone concretions behind. Therefore, a detailed stratigraphy of the sandstone concretions in the study area was not possible.

Size and geometry. Geometrically, the elongate concretions possess three mutually perpendicular axes (a, b, c), all of unequal lengths (Figure 10a). The two longest axes (a and b) are horizontal (parallel to bedding in the sand), and the third (c) is vertical. The a axis is several times the length of the b axis. The b axis is only slightly longer than the c axis. The concretions are oblate perpendicular to the a axis. The degree of departure from the oblate form varies; concretions can be nearly circular to almost tabular in a section normal to the a axis. Ideally, the concretions are uniformly symmetrical along their lengths and taper abruptly at their ends. In some cases, a concretion tapers from a large, bulbous end down to a smaller end. When this occurs, the larger end is the westernmost and the concretion tapers to the east (Figure 11).

The size of the elongate concretions varies considerably, and small concretions may occur adjacent to very large ones. Small concretions may be less than one metre long (a axis) and 20-30 centimetres wide and thick (b and c axes). Dimensions of very large elongate

Fig. 9. Three horizons of elongate sandstone concretions in Bullion Creek Formation. Concretions have merged laterally to form a tabular bed of sandstone. Location is T. 129 N., R. 96 W., sec. 12, SE¼, SW¼, just northeast of Hettinger, North Dakota.

Fig. 10. Geometry of elongate concretions and types of jointing. a) Three axes of concretion geometry; and and b axes are always parallel to bedding. b) Horizontal jointing. c) Radial jointing. d) Concentric jointing. e) Transverse jointing.

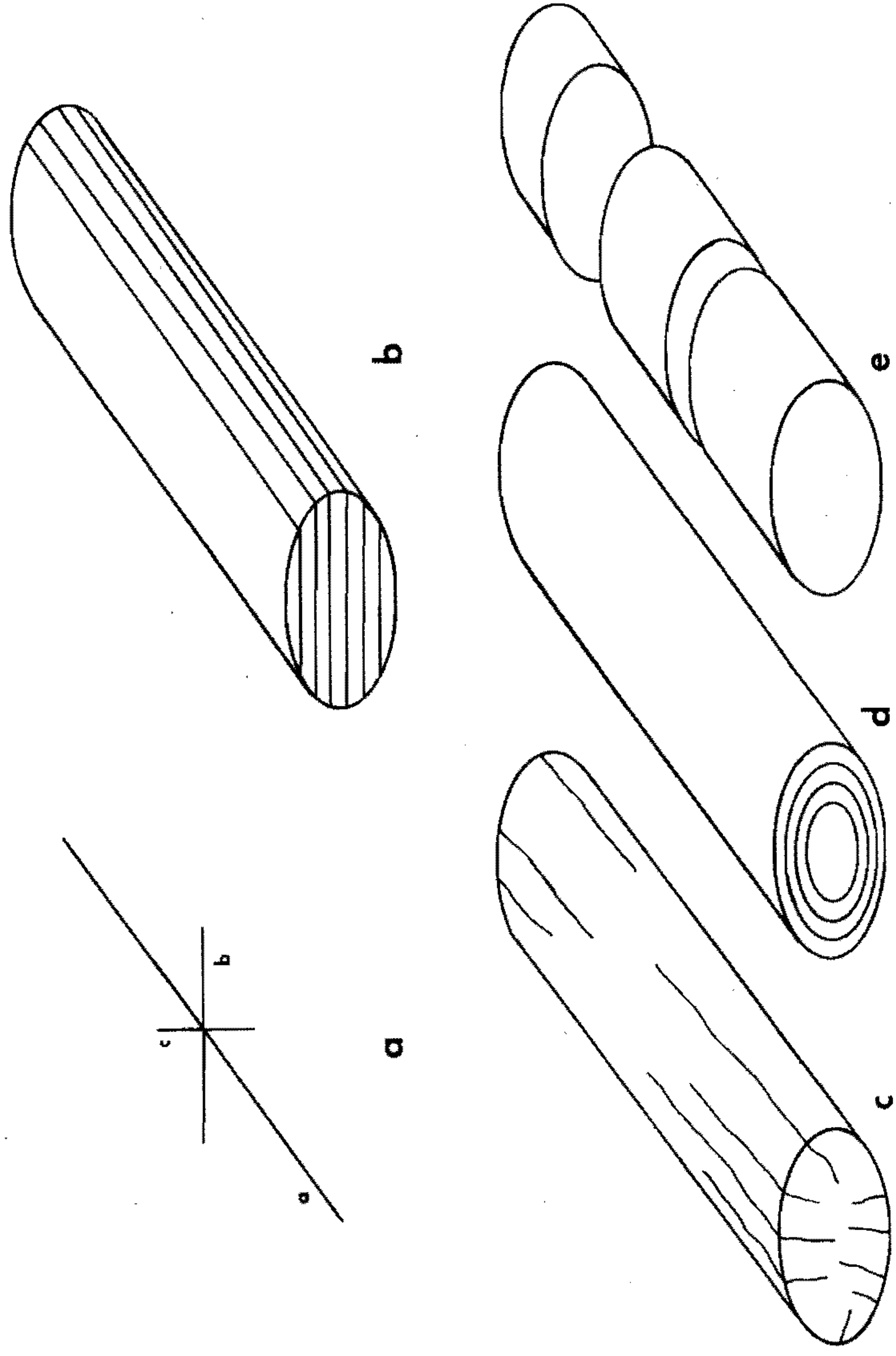


Fig. 11. Elongate sandstone concretion of Slope Formation. Concretion shows transverse fracturing normal to a axis, faint concentric banding on transverse joint face, and exfoliation shells (concentric jointing) on upper surface that parallel concentric banding. Smaller elongate concretion in background has bulbous, western end. Note small, subspherical concretions adjacent to elongate concretion. View is eastward. Location is T. 129 N., R. 92 W., sec. 9, NE¼, NE¼, in gully, 1/4 mile north, 1 mile west of North Lemmon Lake State Game Management Area. Pick is 0.9 m, with 0.1 m divisions.

sandstone concretions are difficult to record, since these features may be only partially exposed or, due to problems of perspective, may not be recognizable as elongate in outcrop. However, a typically large elongate concretion was 2.2 metres thick, 4.5 metres wide, and greater than 16 metres long (the concretion was broken off on one end and covered at the other).

Other types of concretion geometry. Subspherical sandstone concretions are present in the Bullion Creek and Slope sand beds. They are generally smaller than elongate concretions (less than 2 metres in maximum dimension) and often occur adjacent to them (Figure 11). The subspherical concretions contain bedding and sometimes form an irregular sheet in which the original shapes of individual concretions can be recognized. This suggests that isolated individuals have coalesced by continued calcite precipitation. Lithologically, they are very similar to the elongate sandstone concretions.

In places, especially southeast of Hettinger, buttes and ridges are capped by tabular, concretionary sandstone beds. These beds, usually several metres thick, can be traced laterally for hundreds of metres in any direction along a particular butte. They cannot be correlated from one butte to the next. Superimposed on the sandstone beds are parallel alignments of elongated "pinchings" and "swellings." The aligned "swellings" closely resemble individual elongate concretions in size, geometry, and degree of induration, except that they pass laterally or vertically into a tabular sandstone body. On aerial photographs, these features form a rectilinear pattern, similar to isolated elongate concretions. The sandstone "swellings" tend to fracture in the "pinched" areas parallel to their length, due to erosion of underlying material. This fracturing emphasizes their rectilinear appearance on aerial photographs. Generally, this type of concretion is more prevalent in the Bullion Creek Formation than in the Slope Formation.

On aerial photographs of Adams County, large buttes (several square kilometres) capped by sandstone with no rectilinear patterns occur adjacent to individual elongate sandstone concretions and the sandstone beds with "pinchings" and "swellings" described previously. The sandstone is composed of large, irregular bodies that are several metres thick. The bodies are usually connected to one another laterally and vertically. They are encased in sand and are lithologically similar to the elongate and subspherical concretions.

Internal characteristics. The elongate sandstone concretions show four noteworthy internal features: concentric banding, absence of a macroscopic organic nucleus, jointing, and bedding.

Concentric banding in the concretions was observed in several cases. Thicknesses of the bands vary, but generally are less than 8 centimetres. Concentric banding does not extend throughout the concretion; it is confined to the outermost portion (Figure 11).

No organic nucleus was observed in any of the elongate concretions. Macroscopic organic material (as shells and plant remains) commonly forms the nucleus of calcareous sandstone concretions. Organic material may have been present in the elongate concretions, but their large size made inspection of their interior nearly impossible. However, very few shell or plant remains were noted in the sand or sandstone, suggesting this material was not available to serve as nuclei. Some other form of nucleus, perhaps microscopic, must have initiated concretion formation.

Jointing in the elongate concretions is common. Four types of jointing were noted (Figure 10b, c, d, and e): horizontal (joint planes parallel to bedding planes), radial, concentric (curved joint surfaces that parallel concentric banding), and transverse (joint planes perpendicular to the a axis). Transverse jointing is the most common type, followed by horizontal. Radial and concentric jointing are relatively rare. The radial joints are not filled with a secondary mineral and, therefore, should not be confused with septarian structures found in other types of concretions. The elongate concretions sometimes show two types of jointing, but in these cases, one type is invariably transverse. The other three types of jointing do not occur together. The origin of the jointing is discussed in a later section.

Bedding is often preserved in the sandstone concretions. No type of bedding is preserved preferentially. Planar bedding, large- and small-scale cross-bedding, and contorted bedding all occur within the sandstone concretions. In many cases, the bedding passes from the surrounding sand into the concretion (Figure 12).

Lithologic descriptions. On fresh surfaces, the concretionary sandstone is pale yellow or light gray. The sandstone weathers to brown, blackish brown, or gray. The enclosing sand is commonly yellowish-tan to light gray on fresh surfaces.

Texturally, the sandstone concretions and enclosing sand are primarily very fine- to medium-grained (0.0625 mm-0.05 mm). The silt

Fig. 12. Transverse view of two vertically connected, elongate concretions in Bullion Creek Formation. Note continuous plane bedding and horizontal jointing in concretion. View is northeast. Location is T. 129 N., R. 94 W., sec. 25, SW$\frac{1}{4}$, NW$\frac{1}{4}$, at small, sandstone-capped knoll, east side of north-south section line road. Pick is 0.9 m.

content is appreciable, but the amount of clay or clay-sized particles is negligible.

The density of packing differs between the two lithologies. The pre-cementation porosity (the percentage of voids plus void-filling cement) in the sand averages about 29 percent, but about 44 percent in the concretions (Figure 13). Generally, the sand samples also show more grain-to-grain contacts and more deformed grains than the associated sandstone concretions.

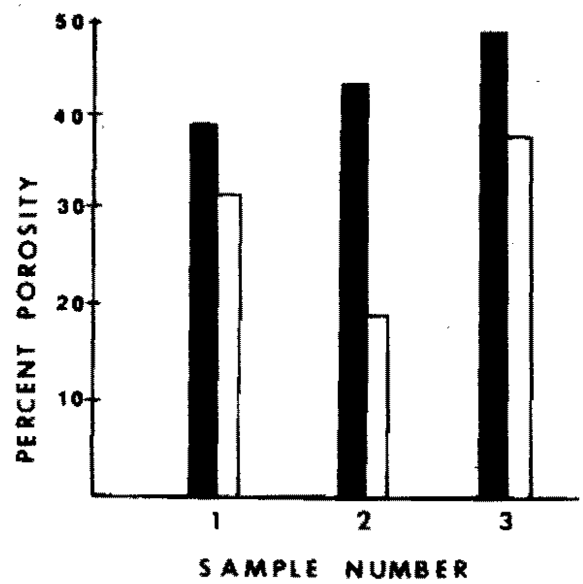
The number of deformed platy grains (mica grains, clay particles) was compared between the two lithologies (Figure 14). In each pair of thin sections, the enclosing sand sample showed more deformation of platy grains, suggesting it had been subjected to more compaction and grain deformation.

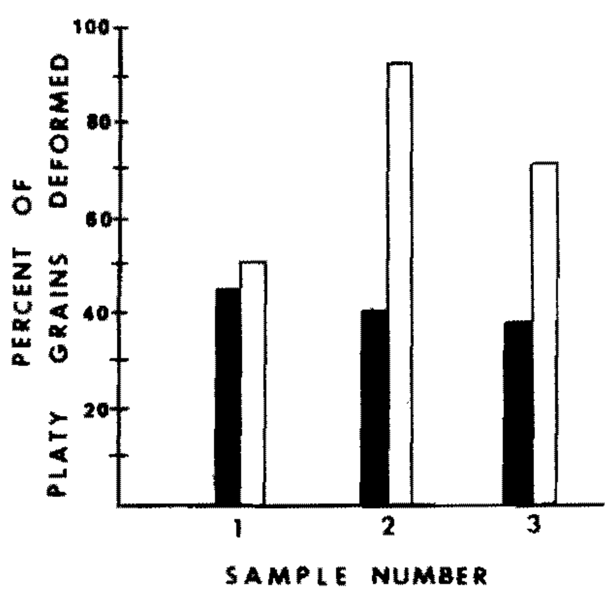
The average composition of three Bullion Creek elongate sandstone concretions and the adjacent sands is shown in Figure 15. The similarity in composition of the sand and sandstone is apparent. The samples contain a high percentage of feldspar grains and rock fragments, indicating compositional immaturity. Using the classification of terrigenous sandtones of Dott (1964), these samples plot near the boundary between arkosic and lithic arenites.

Most of the quartz and feldspar grains of the concretions have been partially replaced by calcite along their perimeters. This gives the grains a slightly pitted outline. The degree of calcite replacement varies from sample to sample, but is never volumetrically significant. This point is also shown by the similarity in composition between the concretionary sandstone and sand. If calcite had formed at the expense

Fig. 13. Percentage of pre-cementation porosity (indicated by cement and voids) in elongate sandstone concretions (black bar) and enclosing sand (white bar). Note higher porosity in concretion. All samples are from Bullion Creek Formation. Locations of samples are given in appendix C (table 4). Raw data are given in appendix C (table 7).

Fig. 14. Percentage of deformed platy grains in elongate sandstone concretions (black bars) and enclosing sand (white bars). All samples are from Bullion Creek Formation. Locations of samples are given in appendix C (table 4). Raw data are given in appendix C (table 8).


50
40
30
20
10
PERCENT POROSITY
1
2
3
SAMPLE NUMBER


100
80
60
40
20
PERCENT OF PLATY GRAINS DEFORMED
1
2
3
SAMPLE NUMBER

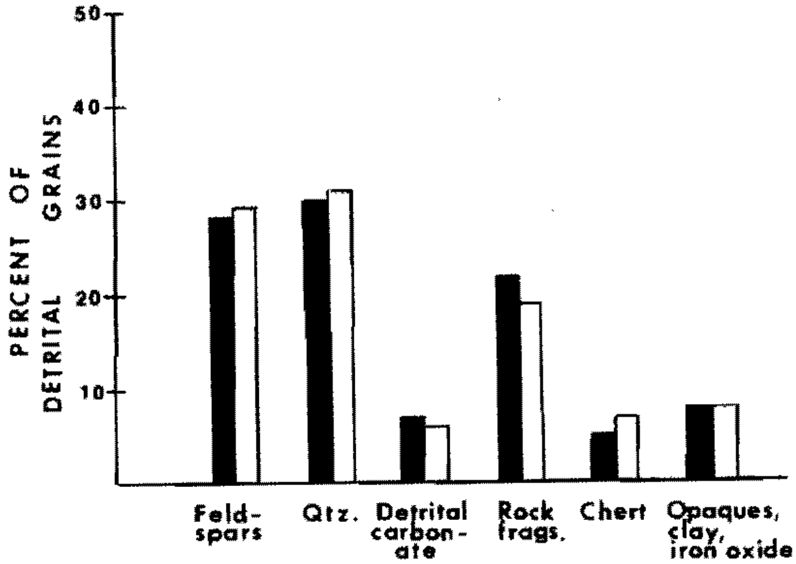



Fig. 15. Average composition of detrital grains of concretionary sandstone (black bars) and enclosing sand (white bars). Note similarity in composition between sand and sandstone. Point count data used in graph are given in appendix C, table 6.

of certain grains, a difference in composition between the two lithologies would be evident.

Many of the feldspar grains are replaced by sericite. There seems to be no significant difference in degree of feldspar weathering between the concretions and the enclosing sand.

The sandstone concretions are cemented with calcium carbonate. The calcite cement has two forms: (1) a large, sparry texture; and (2) a microcrystalline texture. The large crystals are about 0.2 - 0.8 mm in size. They show even extinction upon rotation under crossed polars and often have twin lamellae, indicating they are single crystals. Occasionally, the calcite crystals surround detrital grains, so that the grains appear to float in the cement. In these instances, the cement may be a result of recrystallization of detrital calcite or shell material, and the resulting cement texture may be termed poikilotopic (Scholle 1979). The microcrystalline calcite cement does not have even extinction. When it is present, the alteration of detrital grains (pitted outlines) is more noticeable. Conversely, grains surrounded by large, sparry calcite have a fresher appearance. The relative abundance of the two cement types varies from one sample to the next. Usually, the two types of cement are in contact with one another.

A small amount of microcrystalline calcite cement (less than 20 percent in all cases) is present in thin sections of the sand that encloses the concretions. Instead, the sand is held together primarily by an interlocking grain fabric, a result of post-depositional compaction. This low degree of cementation accounts for the lower resistance to erosion of the enclosing sand and the sharp contact between concretion and sand.

In studying thin sections of calcareous sandstone "log concretions," Frye (1967) found evidence of expansive growth of calcite crystals in the form of (1) broken, displaced feldspar grains separated by fibrous calcite, and (2) sand grains with calcite crystals growing on only one side of the grains. Neither of these two characteristics was noted in the Bullion Creek samples. Hence, expansive growth of calcite probably has been minor in the Bullion Creek sandstone samples.

Other types of cement are rare in the concretions. A very small amount of iron oxide is present as amorphous void fillings. Also, very little clay matrix was noted in thin section.

<u>Other lithologies associated with the concretions</u>. Lenses of conglomerate are present with the sand that surrounds the elongate concretions. The lenses are commonly less than one metre thick and five metres wide. The clasts are composed of angular to rounded, laminated siltstone and claystone. Maximum clast size observed was 40 centimetres. The clasts are more consolidated than the surrounding sand matrix and commonly protrude from the outcrop. However, the clasts are never cemented, either with calcite or iron oxide. The conglomerate lenses are never incorporated into the elongate concretions. In one occurrence, an elongate concretion has begun to form above a conglomerate bed, but has not cemented the underlying conglomerate. This has imparted an irregular transverse shape to the concretion (Figure 16). In outcrop, conglomerate lenses are usually found concealed beneath sandstone ledges, a reflection of their non-indurated character.

Other lithologies present within the sand are thin (less than one metre thick), discontinuous beds of clay and silt. These are also

Fig. 16. Transverse view of elongate concretion in Bullion Creek Formation. Concretion has asymmetric form transverse to the a axis. Conglomerate occurs just below concretion. Note radial jointing in concretion. Location is T. 129 N., R. 95 W., sec. 20, SE¼, NE¼, site of measured section of appendix D, p. 120. Divisions on pick are 0.1 m.

rarely cemented and never incorporated into the concretions. This is probably due to insufficient permeability within the clay and silt.

## Paleocurrent Analysis of Bullion Creek and Slope Formations

Paleocurrent data were collected from concretion-bearing sandstone outcrops to determine whether a relationship exists between paleodrainage and the positions of the elongate concretions. The number of collection sites is limited due to few areas of preserved cross-bedding. The paleocurrent readings obtained are shown in Figure 7 and are listed by location in appendix B (table 3).

Eight of the eleven rose diagrams of Figure 7 (1-5, 7, 9, 10) show a similarity between orientations of the elongate concretions and the associated paleocurrents in Adams County.

# DISCUSSION

The Discussion section of this study is organized in sequential form, starting with the chemical conditions preceding the formation of concretions, moving to their nucleation and growth, and ending with their weathering.

## Sources of the Constituent ions

Two types of sources for the calcium and carbonate ions are likely in the formation of these concretions. The constituent ions may have been derived from within the sand units, or transported relatively great distances by a regional groundwater flow system into the buried Bullion Creek and Slope sand units. There is no evidence that favors either origin conclusively. However, work with modern groundwater flow systems has shown that waters rich in calcium and carbonate ions are relatively "young" and have traveled short distances from the recharge area (Groenewold et al. 1979). Long distances of groundwater migration favor the process of base exchange on clays, where calcium is preferentially removed from the groundwater and replaced by sodium.

Internal sources of ions. Possible sources of calcium and carbonate within the sand units are (1) alteration of feldspars and rock fragments that would release calcium and other ions to the groundwater, (2) dissolution or recrystallization of detrital limestone and dolomite clasts, and (3) entrapment of connate water in the interstices of the sand. Many of the feldspar grains and rock fragments are substantially altered, suggesting they may have been a source of calcium. The presence of poikilotopic calcite cement suggests recrystallization of detrital calcite, but ghost structures of the original grains are rare and many detrital calcite and dolomite grains in the same sample are unaltered. This suggests recrystallization was not a significant source of calcite cement. Surface waters in coal-forming environments like those of the Slope, Bullion Creek, and Sentinel Butte Formations are acidic, a result of the oxidation of organic matter which produces carbonic acid ($H_2CO_3$). Therefore, these waters probably contain calcium and carbonate derived from the dissolution of detrital calcite or shell material in the drainage basin. Their burial would enrich the sand aquifers in these ions. However, it is doubtful that ionic concentrations in the connate waters were sufficient to cause calcite precipitation by themselves because river waters commonly have relatively low concentrations of total dissolved solids (less than 500 parts per million; Livingstone 1964). This is especially true in coal-forming environments like those of the Bullion Creek and Slope Formations, where runoff and dilution are high. Additional sources of calcium and carbonate are required.

External sources of ions. There are several possible external sources of the constituent ions. One is the diffusion of ions from over- and underlying clay beds. Pore waters in nonmarine clay beds are relatively enriched in calcium, carbonate, and other ions relative to the adjacent sand units because of greater porosity, greater grain surface area exposed to the solutions, and more reactive minerals present in the clay. Hence, a concentration gradient would be established, with diffusion from high to low concentrations (from clay beds into the sand beds). Calcium ions would tend to be adsorbed on clay particles and, compared to the carbonate ions, would less likely diffuse. However, since aqueous systems maintain a balance of electrical charges, diffusion of the $CO_3^{--}$ ion would have to be balanced by diffusion of the $Ca^{++}$ ion (or some other positively charged ion) across the concentration gradient.

Vertical leakage of ion-rich groundwater from over- and underlying beds is another source of constituent ions. In the Knife River drainage basin (west-central North Dakota), Groenewold et al. (1979) found that vertical leakage is occurring from surrounding beds into the lower Bullion Creek sand aquifers. This conclusion is based on lower potentiometric values in the sand aquifers compared to those in the surrounding units. Conceivably, this mechanism could have operated in the past, increasing ionic concentrations in the sand aquifers.

Another source of calcium and carbonate is from near-surface environments. Here, the oxidation of organic matter liberates $CO_2$ and $H_2O$ to the groundwater. The carbon dioxide combines with water to form $H_2CO_3$. The reaction is as follows:

$$\underset{\text{(organic matter)}}{CH_2O} + O_2 \longrightarrow CO_2 + H_2O \rightleftarrows \underset{\text{(carbonic acid)}}{H_2CO_3}$$

The presence of carbonic acid lowers the pH of the environment, resulting in the dissolution of detrital calcite and an increase in calcium and carbonate in solution. The dissolution of calcium carbonate is shown in the following reaction:

$$CaCO_3 + \underset{\text{(from carbonic acid)}}{H^+} \rightleftharpoons Ca^{++} + HCO_3^-$$

In using this mechanism of near-surface decomposition of organic matter and dissolution of detrital calcite, one must assume periodic or continual recharge of the underlying sand aquifers, so that concentrations of calcium and carbonate can be built up. This suggests that the sand aquifers could not be buried too deeply, perhaps several hundred feet at most.

## Supersaturation and Precipitation of Calcite

In order to precipitate calcium carbonate cement in sand, supersaturation of the solution with respect to these ions (i.e. a metastable state) must be achieved. The most effective means of supersaturation is the common ion effect (Krauskopf 1967), where the solubility of a certain ion is raised, depending on the ionic strength of the solution. The ionic strength is a measure of the amounts and kinds of ions in a solution. The more abundant and varied are the ions, the greater are the ionic strength and solubility of a given ion.

The most important control on the precipitation of calcite is the pH. Calcite precipitation begins at a pH of approximately 7.8 (Krumbein and Garrels 1952) and becomes widespread above a pH of 8.3 (Hayes 1964), provided sufficient calcium and carbonate are available. The amount of $CO_2$ in solution is a major control of the pH. If the temperature rise or pressure drops, carbon dioxide will be removed from the system. This will lower the concentration of carbonic acid and raise the pH. The following two chemical equations will shift to the left:

$$CaCO_3 + H_2CO_3 \rightleftharpoons 2HCO_3^- + Ca^{++}$$

$$CO_2 + H_2O \rightleftharpoons H_2CO_3$$

The two bicarbonate radicals ($2HCO_3^-$) have been used for two different purposes. One has produced $H_2CO_3$ that later dissociates to yield $CO_2$ and water, and the other has been used to produce $CaCO_3$ (the calcite cement). Hence, these changes will result in calcite precipitation in the sand.

Causes for temperature or pressure changes are speculative. Possibly, a lowering of the regional water table, because of decreased runoff or climatic change, would reduce pressure, thereby permitting $CO_2$ to escape and $CaCO_3$ to precipitate.

## Nucleation and Growth of Concretions

No organic nuclei were noted in the concretions. In many sandstone or shale concretions, organic material forms a nucleus, creating a chemical microenvironment conducive to calcite precipitation in an otherwise inhospitable environment. Apparently, chemical conditions were correct for precipitation throughout the sand units, and the presence of organic material was not required.

Instead, nucleation probably occurred in areas of higher permeability, toward which the constituent ions could diffuse or be transported more easily by flowing groundwater. Freeze and Cherry (1979, p. 153) stated that "permeameter tests on core samples from sandstone strata indicate that the conductivity [a function of permeability] can vary locally by a factor of as much as 10-100 in zones that appear, on the basis of visual inspection, to be relatively homogeneous." Their figure 4.6 (my Figure 17) is a schematic illustration of a vertical

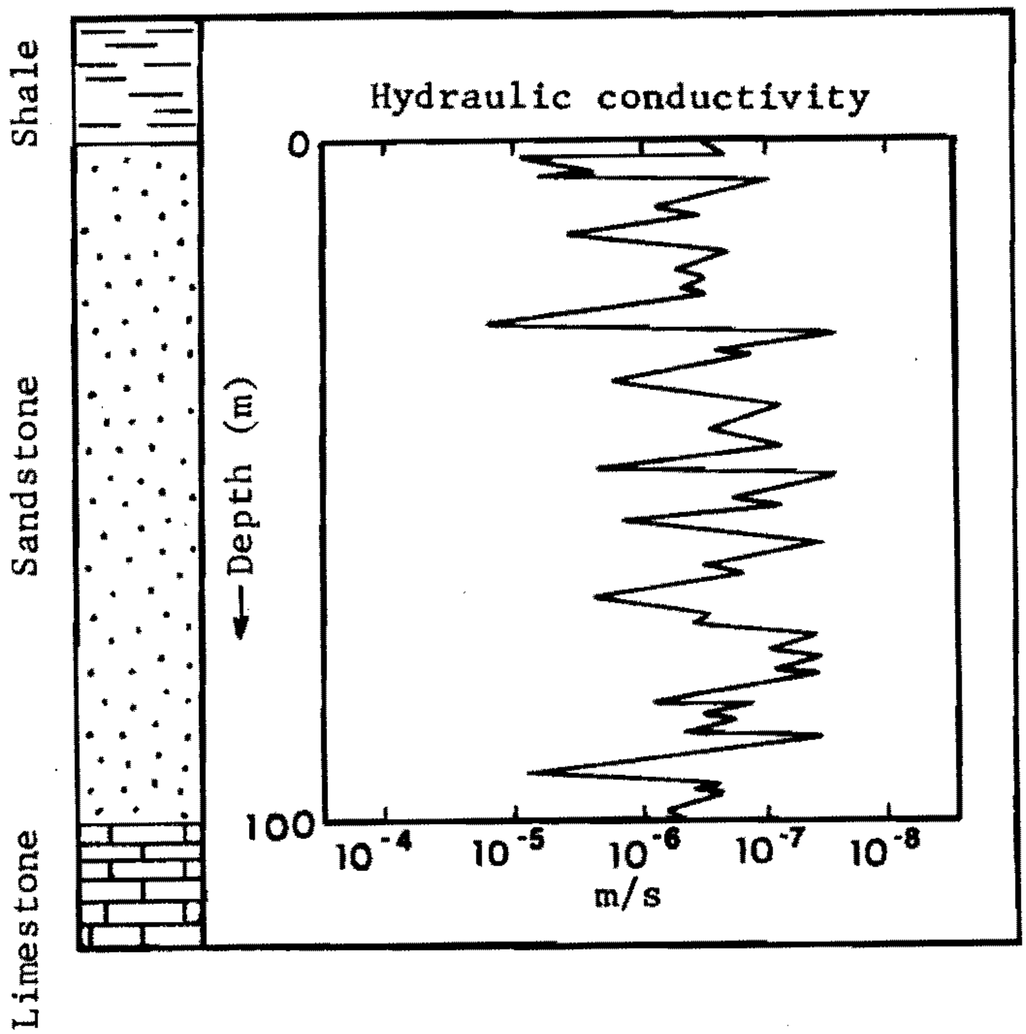



Fig. 17. Schematic diagram of hydraulic conductivity versus depth for a thick, relatively homogeneous sandstone aquifer. Note large variations in conductivity (a function of permeability). From Freeze and Cherry 1979, p. 154.

hydraulic conductivity profile through a thick, relatively homogeneous sandstone. The sharp changes in permeability probably are due to minor changes in depositional conditions or slightly different responses to compaction. The random lateral and vertical variability in sand permeability indicates that sites of concretion growth may also vary considerably and unpredictably.

Deegan (1971) suggested a mechanism to explain the presence of isolated calcium carbonate nuclei in sandstone that subsequently develop into calcareous concretions. He assumed a metastable state with respect to calcium and carbonate ions in solution. If the pH rises rapidly and exceeds 8.3, numerous sites of nucleation will form. Deegan suggested this is analogous to the supercooling of a magma, where large numbers of crystallization sites form, resulting in a uniformly fine-textured rock. Conversely, slow cooling (or a slight rise in pH above 7.8) results in isolated centers of crystal growth. If the pH rises slowly, ionic clusters will have time to form, and a diffusion gradient with respect to calcium and carbonate will be established. The constituent ions will migrate to the sites of nucleation, and, with time, concretions will form.

Calcium and carbonate ions diffusing to the precipitation site form a sphere of influence around the growing concretion. If the spheres of influence of two concretions overlap, one concretion will be robbed of part of its share of constituent ions. This decrease in size of the sphere will result in a reduced growth rate and smaller size for the concretion. The overlapping of diffusion spheres may explain the presence of relatively small elongate concretions adjacent to larger ones (Figure 11). If concentrations of constituent ions are great enough, growth of both concretions will continue, despite the overlap of spheres. The result may be the bundles and beds of elongate concretions observed in certain areas of Adams County (Figure 18).

The presence of two cement textures (large, sparry calcite and microcrystalline calcite) may indicate chemical conditions during precipitation. The large, sparry calcite crystals could be a result of recrystallization of microcrystalline patches of cement; that is, a secondary texture (Krauskopf 1967). Or, in re-applying Deegan's explanation, the two cement textures could be primary if a slow rise in pH above 7.8 in confined areas of the sand gave rise to good crystal development, whereas a rapid pH rise in the other areas resulted in numerous crystallization sites (the microcrystalline texture). The problem with both explanations is whether conditions of recrystallization or pH can vary on such a minute scale that both types of cement are in contact with one another.

Once nucleation has begun and the ionic clusters have developed to a sufficiently large size so that re-solution does not occur, cementation will depend upon the rate at which ions can be delivered to the growth site. This depends upon the permeability of the sand, the rate of groundwater flow, and the concentration of ions in solution.

Variations in the growth rate or the chemistry of the groundwater may explain the presence of concentric banding in the concretions. Presumably, concretions without concentric bands grew at a uniform rate, or under uniform chemical conditions.

Fig. 18. Laterally connected elongate concretions in Bullion Creek Formation. Concretions are oriented northeast-southwest. View is northward. Location is T. 129 N., R. 94 W., sec. 33, NE¼, SW¼, on northeast face of large, sandstone-capped bute, 1/4 mile west of stock pond. Pick (arrow) is 0.9 m long.

## Controls on Shape and Orientation of Concretions

A significant characteristic of these concretions is their elongate shape. Several factors may have enhanced their preferred growth in the direction of the a axis.

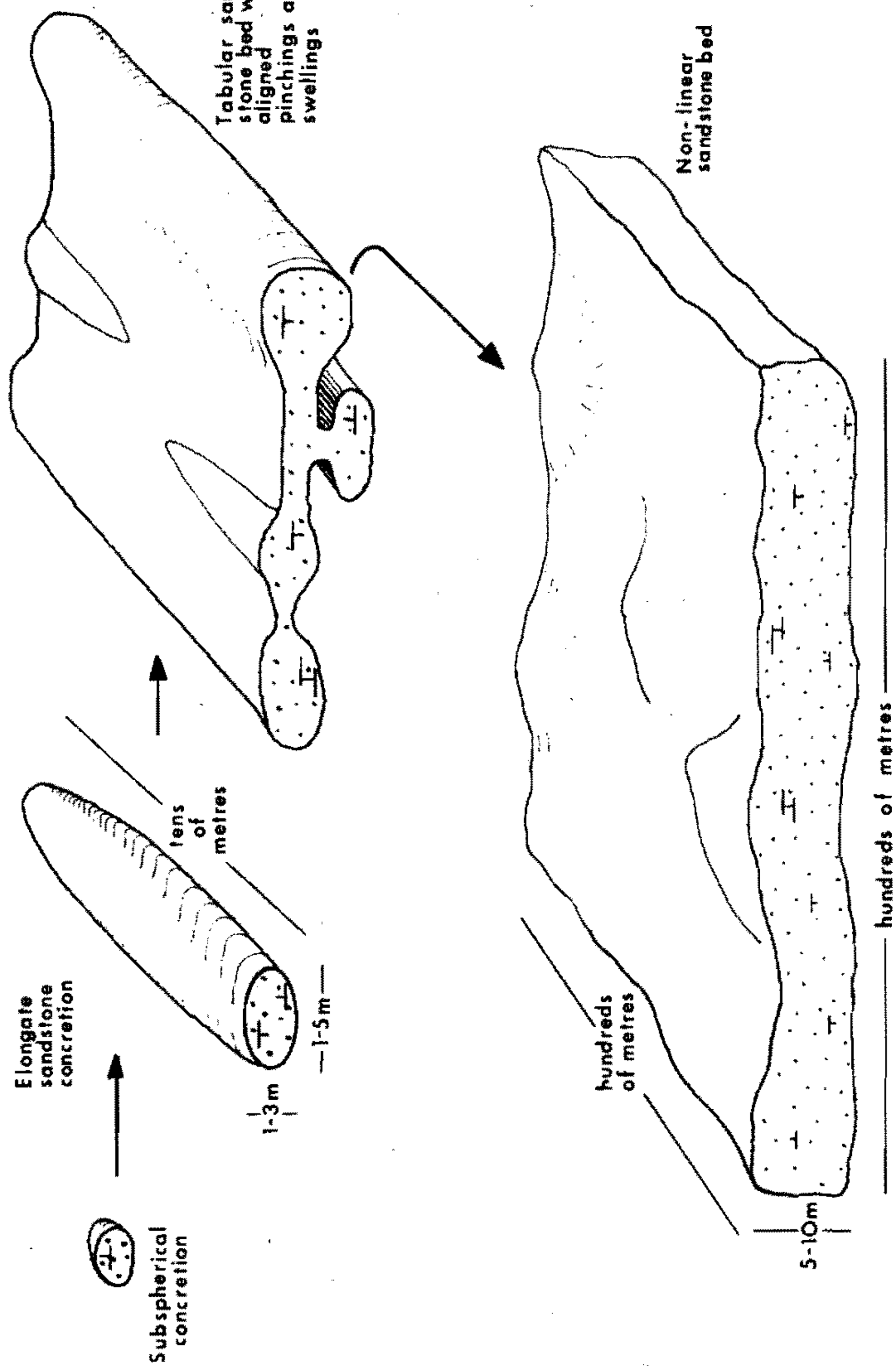
Anisotropic permeability. Compaction of sand by burial decreases vertical permeability, but generally does not effect horizontal permeability. Therefore, growth is favored in lateral directions, resulting in concretions with enhanced horizontal dimensions (a and b axes).

Direction of groundwater flow. The flow of groundwater through the sand units carries calcium and carbonate ions to the sites of concretion growth. Groundwater should flow in the direction of maximum permeability and, therefore, the concretion should grow preferably in this same direction. Fenske (1963) referred to work by Newhouse (1941) on growing isometric crystals in a flowing solution to explain the preferred direction of growth of elongate sandstone concretions. Isometric crystals were used in the experiment so that asymmetric growth could be attributed to external factors, such as the flowing medium, rather than the preferred growth of certain crystal lattice faces. Calcareous sandstone concretions growing in a fluid (groundwater) are analogous to isometric crystals, since neither have inherently preferred growth directions; any asymmetry in shape is due to external influences. Newhouse found that the isometric crystals grew preferentially in the upstream direction, resulting in an asymmetric form, because ions are transported more rapidly by the flowing solution to the site of precipitation. On the downstream side, growth is accomplished only by the slower process of ionic diffusion. Analogously, the concretions also would grow more rapidly in the upstream direction because of more rapid delivery of calcium and carbonate ions. With time, this differential rate of growth will result in a concretion markedly elongated in the direction of the a axis. The elongated axis can then be used as a directional indicator of ancient groundwater flow.

The presence of a large, bulbous end on some of the elongate concretions in Adams County may be related to the differential growth rate. The larger end, the western end in all cases observed, may have been in more direct contact with eastward groundwater flow and, hence, grew more rapidly than the narrower, downstream end. It is unclear to me why a few elongate concretions have a markedly bulbous end, whereas the majority maintain a uniform width and thickness.

Time. Time is a factor that controls the amount of calcite precipitation and, therefore, also controls concretion morphology. Presumably, smaller, subspherical sandstone concretions ceased growing before an elongate form was developed (Figure 19). Conversely, the broad sheets of concretionary sandstone with superimposed "pinchings" and "swellings" in south-central Adams County may represent an advanced stage of concretion growth. In these cases, individual elongate concretions appear to have coalesced laterally, and vertically in some cases, forming a broad, tabular sandstone body. With time and continued calcite precipitation, these sandstone beds could grow to a point where the elongate characteristics are no longer visible. Large areas (several square kilometres) of cemented sandstone having no linear characteristics occur adjacent to elongate concretions in Adams County. This suggests that these various forms of cemented sandstone are points along a continuum that ends in complete diagenetic cementation of the sand. Stevenson (1954) proposed

Fig. 19. Sequence of forms developed by continued sandstone concretion growth. All four types, with many intermediate shapes, are present in Adams County.


Subspherical concretion
Elongate sandstone concretion
1-3m
1-5m
tens of metres
Tabular sandstone bed with aligned pinchings and swellings
Non-linear sandstone bed
hundreds of metres
hundreds of metres
5-10m

that this type of growth pattern of concretions is an early form of diagenetic cementation of sandstone. He suggested that cementation starts at various points (marked by sandstone concretions) and progresses outward in all directions, forming subspherical to lenticular bodies of sandstone. Elongate concretions are one of many types of concretion geometry resulting from this outward growth.

## Controls on Concretion Distribution

The similarity in orientation of the elongate concretions and the associated paleocurrents suggests that the position of buried sand units determined the growth sites of concretions. The sand units may have served as conduits for ancient groundwater from which calcite precipitated to form elongate concretions. Local vagaries of groundwater flow may have caused the discrepancies observed between orientations of elongate concretions and the associated paleocurrents (rose diagrams 6, 8, and 11 of Figure 7). A channel geometry for the sand units would best serve to confine and direct groundwater flow in a specific direction. However, one cannot accurately determine the geometry of the sand units in Adams County because of poor exposure. They may be individual channel sands or portions of a laterally continuous sheet of sand. It is necessary, then, to look at Bullion Creek and Slope sand body geometry in other areas.

In the Medora, North Dakota area, there are two types of sand bodies in the Bullion Creek Formation: linear and tabular (Jacob 1973). The linear sand bodies are up to 300 metres wide and 20 metres thick. They are trough-like in transverse section, and straight and elongate in plan view. They are the more abundant type of sand body. Jacob believed that they originated as low-sinuousity stream deposits. The tabular sand bodies are thinner (3-15 metres) than the linear bodies. Their width is uncertain, but is much greater than that of the linear bodies. Jacob interpreted their origin as laterally-accreting, point bar deposits. The two types of sand bodies may be in close association, but elongate concretions are found only in the linear sand bodies.

In the subsurface of the Knife River basin area (west-central North Dakota), Groenewold et al. (1979, p. 155) noted that "the lower part of the Bullion Creek Formation consists of numerous sand units rather than a single widespread unit." This suggests the presence of individual channel sand deposits rather than a single, continuous sheet sand.

Trapp and Croft (1975) studied the lower part of the Bullion Creek Formation in the subsurface of Hettinger and Stark Counties (southwestern North Dakota). They noted (p. 15) that "a basal sandstone member . . . is persistent, but quite variable in thickness, across the area." The thickness is 50-199 feet. Their aggregate isopach map (figure 3) of the lower Bullion Creek sands shows an alignment of sand thickenings in a northwest-southeast direction. This probably represents the positions of stationary paleochannels. Intervening thinner areas of sand may have been deposited during times of channel migration.

It seems that the lower Bullion Creek and upper Slope sand units commonly have a channel-like geometry. In places, the channels have coalesced laterally to form a sheet of varying thickness. Paleocurrents indicate that the channels have roughly an east-west orientation, as do the concretions. Therefore, in Adams County, the position of paleochannel sands controlled the location of elongate sandstone concretions.

However, the specific location and orientation of a concretion were more directly controlled by subtle differences in permeability.

The location of paleocurrent collection sites 2 through 9 is confined to the south-central portion of the county, from butte-forming sandstone outcrops of approximately the same elevation in the Bullion Creek Formation. The similarity in rose diagrams suggests they may all belong to the same paleochannel system. On aerial photographs, the shape and alignment of sandstone-capped buttes in this area parallels the orientation of the associated concretions, which, in turn, agrees with the paleocurrent orientations. These buttes may, therefore, represent a portion of an exhumed paleochannel in the Bullion Creek Formation.

## Age of the Concretions

Pantin (1958) proposed a three-stage age classification for concretions: syngenetic, diagenetic, and epigenetic. Fenske (1963) subdivided the second stage into early and late. These four subdivisions are based upon field characteristics of the concretions and relationships with the adjacent sediment.

Syngenetic concretions form at the sediment-water interface, at the time of deposition of the enclosing sediment. They may have organism borings on their upper surfaces. They do not have internal primary bedding since they form separately from the sediment. Often, they have asymmetrical shapes in cross section because their upper surface, which is in direct contact with the water, grows more rapidly.

Early and late diagenetic concretions form after deposition of the host sediment, but before compaction and lithification are completed. They may grow at varying depths below the sediment-water interface, and at varying times. Fenske (1963) used the following two criteria in distinguishing early versus late diagenetic concretions: comparison of the degree of compaction of sediment within the concretion with that of the enclosing sediment, and shape of the concretion. Early diagenetic concretions should preserve the original porosity of the sediment and, therefore, show a large difference in compaction when compared to the enclosing sediment. This difference in compaction would be less in late diagenetic concretions, since all sediments were somewhat compacted before concretion formation. The shape of early diagenetic concretions should be spheroidal because of uniform growth in all directions in an uncompacted sediment. Late diagenetic concretions are more ellipsoidal because compaction of the sediment reduces vertical permeability, but horizontal permeability remains unaltered. Thus, lateral growth of the concretion is favored.

Epigenetic concretions are those that form in a host sediment after compaction and lithification are completed.

The Bullion Creek and Slope elongate sandstone concretions cannot be syngenetic in age because they have bedding preserved in their interior. Also, they are symmetrical in cross section with respect to the a and b axes. The absence of animal borings on the upper surfaces is not diagnostic since boring organisms may not have been present at the time of concretion formation.

The presence of bedding within the concretions and their ellipsoidal shape in cross section indicate that they may be late diagenetic in age. An analysis of porosity (Figure 13) and deformation of platy grains (Figure 14) in the concretions and the host sediment substantiates this conclusion. Since the enclosing sand shows evidence of greater compaction than the associated concretion, in the form of less porosity and more deformed platy grains, the concretion formed before the present state of compaction was achieved. But, the concretions show some bending of platy grains and interlocking grain fabric, which is evidence that at least a small amount of compaction occurred before cementation. This rules out an early diagenetic age.

In using porosity (voids and cement) as an indicator of compaction in calcareous sandstone, two assumptions must be made: (1) that replacement of detrital grains by calcite has not been mistaken for void-filling cement, and (2) that expansive growth of calcite has not displaced grains. Although many grains had pitted outlines from calcite replacement, very few were altered beyond recognition. Also, I observed no grains that were shattered and filled with calcite. This indicates the assumptions and interpretations are valid.

The concretions cannot be epigenetic in age because of the porosity differences discussed previously.

## Jointing in the Concretions

The horizontal, radial, and concentric joints in the concretions (Figure 10b-d) are all responses to erosional unloading of overlying sediment, because each type has resulted in an expansion of the concretion. Since horizontal jointing parallels bedding plans, it was controlled by these primary features. Concentric joints may be similar to exfoliation shells, where increased weathering along concentric bands has resulted in the shells splitting away from the concretion (Figure 11). The specific cause for the radial jointing is unknown to me.

The transverse jointing is most likely a later-stage weathering feature than the other joint types because it requires almost total exposure of the concretion. Removal of the underlying, unlithified sand reduces support for the concretion and causes it to fracture normal to the a axis because of its own weight.

## Elongate Concretions as Paleogroundwater Flow Indicators

Since their elongation is controlled by the direction of groundwater flow, the concretions can be used as indicators of paleogroundwater flow direction. If the concretions are well-exposed on aerial photographs, as they are in Adams County, then an indication of regional paleogroundwater flow is given. However, since most concretions in the county do not have bulbous ends, the direction can be either of two, 180 degrees apart. Further evidence, such as indications of paleoslope or structural dip of the strata at the time of concretion formation, must be obtained to determine which direction the groundwater most likely flowed.

In the case of this study, areas of higher relief to the west, indicated by Bullion Creek and Sentinel Butte paleocurrents (Royse 1967), probably acted as recharge areas, and caused gravity-induced groundwater flow to the east through Adams County during the Paleocene Epoch (Figure 20). Buried paleochannels provided routes of maximum permeability, and so the average direction of concretion elongation corresponds to their orientation.

Based on the similar orientations of elongate concretions, The transverse jointing is most likely a later-stage weathering feature than the other joint types because it requires almost total exposure of the concretion. Removal of the underlying, unlithified sand reduces support for the concretion and causes it to fracture normal to the a axis because of its own weight.

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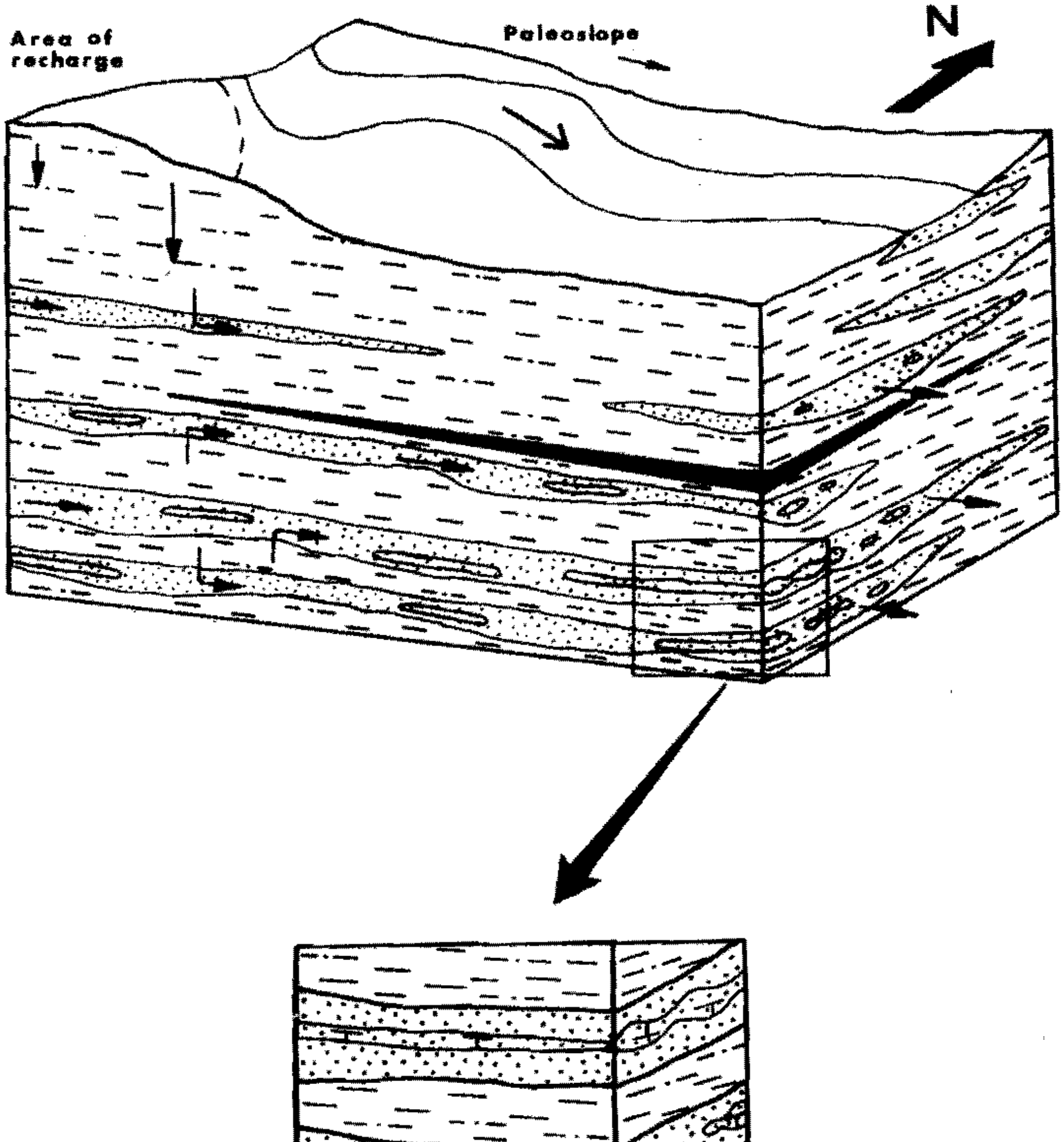
Based on the similar orientations of elongate concretions, associated paleocurrents, and the enclosing channel sand units,

Fig. 20. Interpretive block diagram showing relation between elongate sandstone concretions, paleochannel sands, groundwater flow, and paleoslope in Adams County, North Dakota. Arrows represent directions of groundwater flow. Recharge of groundwater system occurs in elevated areas. Blown-up portion shows elongate sandstone concretions within sand units. Lithologic symbols are those used in Figure 5, except ⊤, which represents calcite cement. All positions of sand, silt, clay, and lignite units are hypothetical. Drawing is not to scale.


Area of recharge
Paleoslope
N

Jacob (1973) proposed the use of elongate concretions for paleochannel indicators. However, given the proper conditions, elongate concretions should be just as likely to form in other types of sand bodies, such as marine sheet sands. In this case, the concretions would be useful only as paleogroundwater flow indicators. Determination of sand unit geometry and collection of paleocurrent data are necessary before elongate concretion orientation can be used to map paleochannel positions.

## CONCLUSIONS

The following conclusions regarding the elongate sandstone concretions were reached during this study:

1. The rectilinear patterns in bedrock, visible on aerial photographs of Adams County, are actually groups of large, elongate, calcareous, sandstone concretions that have been exposed by differential erosion of the surrounding sediment.

2. The concretions have an average east-west orientation.

3. The elongate concretions occur in fluvial channel sand units near the top of the Slope Formation and the base of the Bullion Creek Formation.

4. Elongate concretions usually occur along several discrete horizons that cannot be used as stratigraphic marker beds.

5. The geometry of an elongate concretion can be expressed as three mutually perpendicular axes: the a axis is horizontal and is longest (often greater than 10 metres); the b axis is horizontal and is intermediate in length (1-5 metres); and the c axis is vertical and usually the shortest (1-2 metres). Usually, the concretions have an oblate shape normal to the a axis.

6. The elongate concretions commonly have preserved bedding, indicating a post-depositional origin.

7. The concretions have no observable macroscopic organic nuclei.

8. Some elongate concretions contain concentric banding, which is probably the result of fluctuations in the rate of calcite precipitation or changes in the groundwater chemistry during their growth.

9. Jointing (horizontal, radial, concentric, and transverse) is common in the elongate concretions. All four types are responses to erosional unloading.

10. There are no major differences in composition or texture between the elongate concretions and the enclosing sand, except that the sand has been subjected to more compaction.

11. Two types of calcite cement textures are present in the concretions: microcrystalline and poikilotopic.

12. Paleocurrents in Adams County are generally easterly, parallel to the elongate concretions.

13. The concretions probably formed when groundwater in buried paleochannel sand aquifers became supersaturated with calcium and carbonate, and the pH rose above 7.8.

14. Specific positions of elongate concretion growth probably were determined by subtle differences in permeability. Concretions would form where permeability was greatest.

15. Calcite precipitation in the presence of eastward-flowing groundwater may have resulted in the more rapid growth of the upstream end of the concretion. The result would be an elongate form with an east-west orientation.

16. Continued concretion growth may have resulted in laterally connected elongate concretions, and, eventually, in tabular sandstone sheets having no recognizable linear form.

17. The age of the concretions is probably late diagenetic.

18. During the time of concretion formation, groundwater probably flowed west to east in Adams County, in response to the paleoslope. Groundwater flow roughly followed the positions of buried channel sands, since these acted as paths of maximum permeability.

19. Elongate sandstone concretions can be used as paleogroundwater flow indicators.

# APPENDICES

# APPENDIX A

## LOCATIONS, ORIENTATIONS, AND NUMBER OF ELONGATE SANDSTONE CONCRETIONS

## Locations, Orientations, and Number of Elongate Sandstone Concretions

Appendix A consists of table 2, which is a list of the locations, orientations (measured in degrees), and number of elongate concretions visible on aerial photographs and used in Plate 1, Figure 7, and table 1. The frequency refers to the number that is associated with each line segment on Plate 1; it is the quantity of concretions that have the same orientation. The asterisks denote the 50 square-mile sections used to construct Figure 7 and table 1.

TABLE 2

LOCATIONS, ORIENTATIONS, AND NUMBER OF ELONGATE SANDSTONE CONCRETIONS

| Township | Range | Section | ¼ section | Azimuth | Frequency |
|---|---|---|---|---|---|
| 129N | 91W | 4 | NW | 83 | 4 |
| | | 4 | SE | 76 | 5 |
| | | 4 | SW | 79 | 6 |
| | | 9 | SW | 78 | 5 |
| | | 10 | SE | 65 | 4 |
| | | *15 | NE | 51 | 9 |
| | | *15 | NE | 27 | 2 |
| | | *15 | NW | 79 | 8 |
| | | *15 | NW | 86 | 9 |
| | | 32 | SE | 68 | 2 |
| | | 33 | SW | 51 | 10 |
| 129N | 92W | 1 | NE | 66 | 7 |
| | | *2 | SW | 70 | 12 |
| | | *2 | SW | 86 | 8 |
| | | 3 | NE | 145 | 2 |
| | | 3 | NE | 130 | 5 |
| | | 3 | SW | 76 | 5 |
| | | 3 | SW | 111 | 18 |
| | | 4 | SW | 85 | 3 |
| | | 5 | SE | 93 | 7 |
| | | 5 | SE | 88 | 3 |
| | | 9 | NW | 96 | 13 |
| | | 9 | SW | 95 | 4 |
| | | 9 | SW | 120 | 5 |
| | | *10 | NE | 95 | 3 |
| | | *10 | SW | 90 | 11 |
| | | *10 | SW | 89 | 19 |
| | | *11 | NE | 79 | 65 |
| | | *11 | SW | 87 | 13 |

TABLE 2--Continued

| Township | Range | Section | ¼ section | Azimuth | Frequency |
|---|---|---|---|---|---|
| 129N | 92W | 14 | NE | 46 | 15 |
| | | 14 | SE | 65 | 9 |
| | | 14 | SE | 76 | 1 |
| | | 14 | SE | 96 | 2 |
| | | 16 | NW | 106 | 19 |
| | | 28 | NW | 82 | 3 |
| 129N | 93W | 1 | NE | 95 | 18 |
| | | 4 | SW | 59 | 5 |
| | | 6 | NW | 61 | 7 |
| | | * 7 | SW | 46 | 7 |
| | | 8 | NW | 68 | 11 |
| | | 17 | SW | 64 | 3 |
| | | 19 | SW | 50 | 13 |
| | | 30 | NW | 56 | 2 |
| | | 30 | NW | 67 | 7 |
| | | 36 | NE | 118 | 3 |
| | | 36 | NE | 129 | 3 |
| 129N | 94W | 4 | NE | 82 | 1 |
| | | 5 | NW | 60 | 3 |
| | | *12 | SW | 48 | 3 |
| | | 12 | SW | 69 | 4 |
| | | 22 | SW | 43 | 1 |
| | | 22 | SW | 55 | 4 |
| | | *24 | NW | 60 | 17 |
| | | 24 | NE | 65 | 7 |
| | | 24 | NW | 55 | 6 |
| | | 24 | NE | 52 | 8 |
| | | *25 | NW | 60 | 2 |
| | | 25 | NE | 32 | 11 |
| | | 25 | SW | 45 | 33 |

TABLE 2--Continued

| Township | Range | Section | ¼ section | Azimuth | Frequency |
|---|---|---|---|---|---|
| 129N | 94W | 28 | NW | 85 | 3 |
| | | 28 | NE | 71 | 2 |
| | | 28 | SW | 53 | 2 |
| | | 28 | SW | 76 | 10 |
| | | 29 | SE | 114 | 3 |
| | | 29 | SE | 94 | 4 |
| | | 29 | SW | 77 | 4 |
| | | 30 | SE | 92 | 43 |
| | | 30 | NW | 120 | 7 |
| | | 30 | SW | 110 | 3 |
| | | * 31 | SW | 70 | 3 |
| | | 31 | SW | 88 | 7 |
| | | * 32 | NW | 96 | 5 |
| | | 33 | NE | 76 | 41 |
| | | 33 | SW | 63 | 12 |
| | | * 33 | NE | 65 | 4 |
| | | 33 | NE | 70 | 10 |
| | | 33 | SW | 81 | 3 |
| | | 34 | SE | 60 | 28 |
| | | 34 | SE | 65 | 9 |
| | | 34 | SE | 54 | 4 |
| | | 34 | SE | 80 | 2 |
| | | 35 | SW | 42 | 4 |
| 129N | 95W | * 12 | SW | 66 | 4 |
| | | 12 | SW | 60 | 7 |
| | | * 15 | SW | 73 | 8 |
| | | 19 | NW | 114 | 9 |
| | | 19 | NE | 117 | 4 |
| | | 19 | NE | 130 | 7 |
| | | 19 | NE | 111 | 2 |
| | | 20 | NE | 96 | 20 |
| | | 20 | SE | 86 | 11 |
| | | 20 | SE | 67 | 3 |
| | | 20 | SE | 88 | 9 |
| | | 20 | SE | 91 | 3 |
| | | 20 | SE | 75 | 6 |

TABLE 2--Continued

| Township | Range | Section | ¼ section | Azimuth | Frequency |
|---|---|---|---|---|---|
| 129N | 95W | 21 | NE | 110 | 5 |
| | | 21 | SE | 91 | 5 |
| | | 21 | NE | 78 | 5 |
| | | *21 | SW | 101 | 4 |
| | | 21 | SW | 115 | 19 |
| | | 21 | SE | 96 | 13 |
| | | 21 | SE | 117 | 16 |
| | | 21 | SE | 87 | 1 |
| | | 24 | SW | 117 | 4 |
| | | 24 | SW | 126 | 13 |
| | | *24 | SW | 135 | 16 |
| | | 24 | SE | 97 | 4 |
| | | 24 | SW | | 4 |
| | | *25 | NE | 129 | 12 |
| | | 25 | NE | 138 | 3 |
| | | 26 | NW | 94 | 13 |
| | | 26 | NW | 78 | 14 |
| | | *26 | NW | 89 | 11 |
| | | 26 | NE | 56 | 12 |
| | | 26 | NE | 73 | 6 |
| | | 27 | NE | 129 | 6 |
| | | *27 | SW | 174 | 4 |
| | | 27 | SW | 130 | 8 |
| | | 28 | NE | 92 | 6 |
| | | *28 | NE | 81 | 4 |
| | | 28 | SE | 108 | 3 |
| | | 36 | SE | 59 | 2 |
| | | 36 | SE | 69 | 3 |
| | | 36 | SW | 75 | 4 |
| 129N | 96W | 7 | SW | 69 | 1 |
| | | *7 | SW | 81 | 1 |
| | | 7 | SE | 76 | 30 |
| | | 12 | SE | 79 | 6 |
| | | *12 | SE | 69 | 7 |
| | | 12 | SE | 54 | 3 |

TABLE 2--Continued

| Township | Range | Section | ¼ section | Azimuth | Frequency |
|---|---|---|---|---|---|
| 129N | 96W | 14 | NW | 92 | 7 |
| | | 14 | NW | 97 | 3 |
| | | 14 | NW | 102 | 18 |
| | | 15 | NW | 111 | 16 |
| | | 15 | SE | 56 | 3 |
| | | 16 | SE | 95 | 4 |
| | | 17 | SE | 87 | 1 |
| | | 17 | SE | 63 | 1 |
| | | 17 | SE | 47 | 3 |
| | | * 18 | NE | 90 | 14 |
| | | * 19 | NE | 39 | 9 |
| | | 19 | NE | 24 | 7 |
| | | 19 | SW | 61 | 2 |
| | | 19 | SW | 55 | 4 |
| | | 21 | NE | 69 | 7 |
| | | 21 | NE | 84 | 3 |
| | | * 27 | NE | 62 | 3 |
| | | 27 | NE | 22 | 4 |
| | | 27 | NE | 29 | 16 |
| | | 30 | NW | 53 | 8 |
| | | 30 | NW | 74 | 3 |
| | | 36 | SE | 70 | 6 |
| 129N | 97W | * 13 | NE | 97 | 5 |
| | | 14 | NW | 67 | 6 |
| | | 14 | NW | 73 | 10 |
| | | 14 | NW | 81 | 4 |
| | | * 15 | SW | 60 | 5 |
| | | 23 | SW | 70 | 5 |
| 129N | 98W | * 5 | SE | 46 | 9 |
| | | 5 | SE | 53 | 7 |

TABLE 2--Continued

| Township | Range | Section | ¼ section | Azimith | Frequency |
|---|---|---|---|---|---|
| 130N | 93W | 28 | NW | 115 | 4 |
| | | 28 | NW | 106 | 9 |
| | | 28 | NW | 100 | 3 |
| | | * 29 | SE | 92 | 10 |
| | | 29 | SW | 72 | 4 |
| | | 35 | SE | 94 | 4 |
| | | * 36 | NE | 78 | 5 |
| | | 36 | SW | 88 | 8 |
| 130N | 94W | 7 | NW | 92 | 11 |
| | | 7 | NE | 99 | 2 |
| | | * 8 | NW | 90 | 10 |
| | | 8 | NW | 109 | 13 |
| | | 8 | NW | 113 | 6 |
| | | 8 | NE | 85 | 5 |
| | | 9 | SE | 106 | 11 |
| | | 11 | SW | 99 | 4 |
| | | 11 | SE | 103 | 8 |
| | | 11 | SE | 125 | 7 |
| | | 13 | SE | 93 | 3 |
| | | 14 | NE | 143 | 20 |
| | | 14 | NE | 163 | 3 |
| | | 14 | NE | 165 | 4 |
| | | 14 | NE | 31 | 3 |
| | | 16 | NW | 70 | 4 |
| | | 24 | NE | 66 | 2 |
| | | * 33 | SE | 45 | 15 |
| 130N | 95W | * 12 | NW | 89 | 13 |
| | | 12 | NW | 86 | 5 |
| | | 12 | NW | 97 | 6 |
| | | 12 | NE | 95 | 6 |
| | | 16 | NE | 102 | 1 |
| | | 16 | NE | 95 | 8 |

TABLE 2--Continued

| Township | Range | Section | ¼ section | Azimuth | Frequency |
|---|---|---|---|---|---|
| 129N | 98W | * 35 | SE | 318 | 7 |
| 130N | 91W | * 32 | SE | 123 | 5 |
| | | 33 | SE | 106 | 2 |
| | | 33 | SE | 93 | 2 |
| 130N | 92W | 4 | NW | 319 | 1 |
| | | 4 | NW | 314 | 1 |
| | | 4 | NW | 300 | 1 |
| | | 6 | SW | 128 | 2 |
| | | 7 | NW | 131 | 3 |
| | | 7 | NW | 134 | 8 |
| | | 7 | SW | 112 | 2 |
| | | 7 | SW | 116 | 2 |
| | | 7 | SW | 119 | 7 |
| | | 33 | SW | 143 | 3 |
| | | 35 | SW | 129 | 2 |
| 130N | 93W | 1 | SW | 142 | 13 |
| | | 1 | SW | 160 | 3 |
| | | 1 | SW | 120 | 5 |
| | | 2 | SE | 137 | 17 |
| | | 12 | NW | 147 | 5 |
| | | 19 | NW | 92 | 3 |
| | | 20 | SW | 130 | 1 |
| | | 21 | SW | 95 | 4 |
| | | 24 | SW | 46 | 1 |
| | | 24 | SE | 66 | 2 |
| | | 25 | NE | 120 | 2 |
| | | * 26 | SW | 83 | 5 |

TABLE 2—Continued

| Township | Range | Section | ¼ section | Azimuth | Frequency |
|---|---|---|---|---|---|
| 130N | 95W | 17 | NE | 89 | 5 |
| | | 17 | NE | 75 | 2 |
| | | *18 | NW | 77 | 2 |
| | | *18 | NW | 90 | 5 |
| | | *18 | NW | 86 | 2 |
| | | *18 | SW | 70 | 15 |
| | | *18 | SW | 50 | 5 |
| | | *18 | SW | 65 | 5 |
| | | *24 | NW | 112 | 9 |
| | | *24 | NE | 87 | 4 |
| | | 30 | SW | 24 | 5 |
| | | 30 | SW | 39 | 8 |
| 130N | 96W | 2 | SW | 42 | 6 |
| | | 2 | SW | 68 | 5 |
| | | *4 | NW | 105 | 3 |
| | | *4 | NW | 139 | 3 |
| | | 7 | NW | 57 | 3 |
| | | 13 | SE | 45 | 1 |
| | | 16 | NW | 93 | 5 |
| | | 25 | SW | 41 | 5 |
| | | 25 | SE | 56 | 8 |
| | | 25 | SE | 67 | 3 |
| | | *26 | SE | 45 | 4 |
| | | *26 | SE | 27 | 4 |
| | | 27 | SE | 48 | 9 |
| | | 27 | SE | 68 | 7 |
| | | 27 | SE | 54 | 5 |
| | | 34 | SE | 50 | 5 |
| | | 35 | NW | 43 | 24 |
| | | 35 | NW | 49 | 21 |
| | | 35 | NE | 47 | 14 |

TABLE 2--Continued

| Township | Range | Section | ¼ section | Azimuth | Frequency |
|---|---|---|---|---|---|
| 130N | 96W | 36 | NW | 8 | 4 |
| | | 36 | NW | 17 | 4 |
| | | 36 | NW | 35 | 24 |
| | | 36 | NE | 25 | 9 |
| | | * 36 | NE | 31 | 6 |
| | | 36 | NE | 39 | 6 |
| | | 36 | SE | 80 | 7 |
| | | 36 | SW | 97 | 3 |
| | | 36 | SW | 116 | 9 |
| 130N | 97W | 21 | SW | 165 | 3 |
| | | * 23 | NW | 52 | 8 |
| | | * 25 | SW | 75 | 9 |
| | | * 27 | NE | 146 | 11 |
| | | 28 | NW | 45 | 5 |
| | | 29 | NE | 75 | 6 |
| | | 31 | SW | 75 | 6 |
| | | 31 | SW | 90 | 7 |
| | | 35 | SW | 132 | 5 |
| 130N | 98W | 8 | NW | 87 | 5 |
| | | 8 | NW | 102 | 3 |
| | | 8 | SW | 97 | 6 |
| | | * 8 | SW | 84 | 7 |
| | | 8 | SW | 115 | 5 |
| | | 8 | SW | 128 | 2 |
| | | 8 | SE | 66 | 9 |
| | | * 9 | NE | 74 | 4 |
| | | 9 | NE | 72 | 5 |
| | | 10 | NW | 93 | 6 |
| | | 10 | NW | 108 | 5 |
| | | 10 | SW | 72 | 8 |
| | | 10 | SW | 66 | 8 |
| | | 10 | SW | 94 | 11 |
| | | 10 | SE | 85 | 10 |
| | | 10 | SE | 91 | 11 |
| | | 10 | SW | 92 | 9 |

TABLE 2--Continued

| Township | Range | Section | ¼ section | Azimuth | Frequency |
|---|---|---|---|---|---|
| 130N | 98W | * 12 | SW | 90 | 17 |
| | | 13 | SW | 120 | 8 |
| | | 14 | NE | 97 | 5 |
| | | 14 | NE | 81 | 3 |
| | | * 14 | NE | 72 | 2 |
| | | 14 | SW | 108 | 6 |
| | | 14 | SW | 120 | 10 |
| | | 14 | SE | 148 | 9 |
| | | 15 | NW | 85 | 5 |
| | | * 15 | NE | 55 | 8 |
| | | 15 | NE | 100 | 17 |
| | | 16 | NW | 90 | 17 |
| | | 16 | NW | 46 | 21 |
| | | 16 | NE | 118 | 3 |
| | | 16 | NE | 155 | 11 |
| | | 16 | NW | 68 | 23 |
| | | 16 | NE | 14 | 9 |
| | | 18 | SE | 51 | 8 |
| | | 18 | SE | 68 | 3 |
| | | 27 | NE | 89 | 9 |
| | | 34 | NE | 63 | 2 |
| | | 34 | NE | 75 | 3 |
| | | 36 | SE | 71 | 18 |
| | | 36 | SE | 75 | 5 |
| 131N | 92W | 29 | SE | 153 | 1 |
| | | 29 | SE | 138 | 3 |
| | | 34 | SW | 122 | 5 |
| 131N | 93W | 27 | SW | 135 | 10 |
| | | 27 | SE | 125 | 9 |
| | | 28 | NW | 107 | 2 |
| | | 28 | SW | 138 | 8 |

TABLE 2--Continued

| Township | Range | Section | ¼ section | Azimuth | Frequency |
|---|---|---|---|---|---|
| 131N | 93W | 34 | NW | 140 | 4 |
| | | 34 | NW | 161 | 9 |
| | | 34 | SW | 147 | 18 |
| | | 34 | SW | 170 | 3 |
| 131N | 94W | 6 | SW | 28 | 2 |
| 131N | 95W | 4 | SE | 88 | 2 |
| | | 4 | SE | 91 | 3 |
| | | 5 | NE | 76 | 3 |
| | | 7 | SW | 61 | 9 |
| | | 7 | SW | 50 | 1 |
| | | 7 | SE | 64 | 9 |
| | | 10 | NE | 78 | 5 |
| | | 31 | NE | 71 | 4 |
| 131N | 96W | 6 | SW | 79 | 6 |
| | | * 8 | NE | 149 | 9 |
| | | 35 | SE | 52 | 6 |
| 131N | 97W | 17 | SE | 126 | 1 |
| | | * 26 | SW | 109 | 2 |
| | | 26 | SW | 95 | 5 |
| | | 26 | SE | 75 | 3 |
| | | 26 | SE | 87 | 2 |
| 132N | 95W | 19 | SW | 102 | 1 |
| | | 19 | SW | 85 | 2 |
| | | 30 | SE | 31 | 5 |
| | | 33 | SW | 64 | 2 |
| | | 33 | SW | 52 | 27 |
| 132N | 98W | 33 | SW | 67 | 1 |
| | | 36 | SW | 132 | 3 |

APPENDIX B

PALEOCURRENT DATA

## Paleocurrent Data

Appendix B consists of table 3, which is a list of cross-bed azimuths, their collection locations, vector means ($\bar{\alpha}$) (measured in degrees), vector strengths ($\bar{a}$), and stratigraphic position. BC denotes those readings taken from the Bullion Creek Formation; SL represents those azimuths from the Slope Formation. The number of readings taken is represented by n. PRD refers to the paleocurrent rose diagrams in Figure 7 and indicates which data set was used to construct each rose diagram. The mathematical handling of the paleocurrent data is explained in the Methods section of the text (p. 15).

TABLE 3

PALEOCURRENT DATA

| Twnshp. | Rng. | Sec. | Fm. | n | $\bar{\alpha}$ | $\bar{a}$ | PRD | Values |
|---|---|---|---|---|---|---|---|---|
| 130N | 95W | 30 | BC | 13 | 30 | 0.81 | 1 | 8, 38, 5, 85, 62, 22, 345, 346, 355, 5, 82, 45, 85 |
| 129N | 95W | 19 | BC | 21 | 116 | 0.66 | 2 | 152, 125, 145, 115, 115, 105, 55, 125, 145, 235, 85, 105, 145, 78, 155, 225, 0, 142, 95, 82, 35 |
| 129N | 95W | 20 | BC | 74 | 90 | 0.74 | 4 | 135, 70, 85, 332, 133, 102, 116, 155, 107, 15, 25, 64, 117, 95, 112, 55, 345, 78, 95, 205, 71, 66, 55, 175, 22, 115, 55, 98, 176, 55, 121, 116, 110, 85, 355, 135, 95, 95, 54, 69, 36, 112, 42, 125, 83, 125, 75, 48, 95, 125, 75, 115, 68, 110, 75, 129, 145, 106, 96, 110, 136, 113, 62, 61, 120, 57, 29, 86, 305, 129, 104, 54, 125, 78 |
| 129N | 95W | 24 | BC | 70 | 107 | 0.67 | 5 | 142, 110, 175, 145, 145, 75, 111, 115, 120, 74, 64, 166, 95, 141, 45, 33, 123, 75, 51, 145, 45, 115, 15, 115, 145, 95, 90, 115, 145, 355, 125, 104, 188, 270, 145, 275, 115, 95, 105, 75, 105, 76, 128, 106, 193, 225, 165, 95, 65, 73, 106, 165, 350, 87, 78, 178, 120, 135, 36, 25, 115, 64, 152, 134, 78, 122, 130, 123, 45, 95 |
| 129N | 95W | 20 | BC | 13 | 74 | 0.77 | 3 | 75, 88, 128, 115, 35, 125, 325, 75, 74, 40, 50, 95, 52 |
| 129N | 94W | 30 | BC | 34 | 84 | 0.42 | 6 | 335, 35, 113, 90, 125, 155, 112, 298, 275, 15, 111, 42, 285, 165, 95, 85, 125, 358, 45, 145, 45, 45, 305, 55, 48, 235, 95, 191, 205, 85, 85, 95, 105, 91 |
| 129N | 94W | 33 | BC | 43 | 70 | 0.73 | 7 | 185, 95, 50, 65, 65, 80, 55, 55, 80, 70, 68, 75, 105, 87, 135, 95, 45, 75, 93, 15, 12, 85, 85, 345, 95, 52, 15, 35, 65, 25, 135, 75, 95, 85, 110, 25, 25, 260, 258, 84, 95, 105 |

TABLE 3--Continued

| Twnshp. | Rng. | Sec. | Fm. | n | $\bar{\alpha}$ | $\bar{a}$ | PRD | Values |
|---|---|---|---|---|---|---|---|---|
| 129N | 94W | 34 | BC | 47 | 156 | 0.48 | 8 | 175, 175, 165, 105, 178, 254, 157, 221, 225, 95, 215, 195, 125, 142, 110, 120, 15, 85, 186, 175, 125, 248, 208, 196, 210, 215, 235, 125, 191, 159, 85, 115, 255, 272, 65, 66, 35, 81, 38, 138, 68, 28, 188, 215, 95, 147, 195 |
| 129N | 94W | 36 | BC | 30 | 1 | 0.69 | 9 | 130, 20, 78, 66, 105, 65, 55, 340, 325, 285, 325, 302, 308, 54, 335, 15, 355, 55, 335, 345, 325, 315, 329, 25, 345, 8, 330, 8, 5, 345 |
| 129N | 92W | 16 | BC | 17 | 53 | 0.71 | 10 | 345, 45, 65, 19, 88, 52, 45, 142, 5, 65, 135, 45, 54, 25, 91, 90, 316 |
| 129N | 92W | 10 | SL | 20 | 150 | 0.3 | 11 | 65, 47, 139, 76, 5, 322, 155, 208, 170, 108, 175, 115, 328, 64, 211, 135, 181, 235, 250, 215 |

# APPENDIX C

# POINT COUNT DATA

## Point Count Data

Appendix C consists of tables 4 through 8. These tables list the results of petrographic analyses of six thin sections of elongate sandstone concretions and the enclosing sand. All samples were collected from the Bullion Creek Formation. The sandstone concretions are labeled with an a and the sand samples with a b.

Table 4 gives information on the sample collection sites. Table 5 gives the point count data in raw form. Table 6 shows the percentages of detrital grains in each sample. The counts of cement and voids were excluded, and the remaining detrital grain counts were normalized to 100 percent. This was done to determine whether significant differences in composition exist between the concretion and sand samples. The information of table 6 was used to construct Figure 15. Table 7 shows the differences in porosity between the sand and sandstone concretion. The table was constructed by summing the cement and void counts for each sample and normalizing to 100 percent. This information was used to construct Figure 13. Table 8 is the result of counting platy grains and classifying them as deformed or undeformed. The percentage of deformed platy grains was calculated; it is shown graphically in Figure 14.

TABLE 4

SAMPLE COLLECTION SITES

| Sample Number | Location | Elevation (feet) |
|---|---|---|
| 1a and 1b | T129N, R97W, s15, SE¼, NW¼ | 2930 |
| 2a and 2b | T23N, R14E, s20, NW¼, NW¼ (Perkins Co., S.D.) | 2670 |
| 3a and 3b | T130N, R98W, s15, NE¼, NW¼ | 2820 |

TABLE 5

POINT COUNT DATA ON DETRITAL GRAINS

| Rock Components | Sample Number | | | | | |
|---|---|---|---|---|---|---|
| Feldspars | 21 | 27 | 35 | 45 | 38 | 49 |
| Quartz | 43 | 58 | 25 | 40 | 32 | 32 |
| Detrital carbonate | 12 | 14 | 4 | 7 | 6 | 5 |
| Rock fragments | 29 | 18 | 33 | 40 | 12 | 25 |
| Chert | 10 | 13 | 1 | 8 | 5 | 8 |
| Opaques + iron oxide | 8 | 8 | 15 | 22 | 8 | 6 |
| Cement | 56 | 28 | 83 | 2 | 73 | 36 |
| Voids | 21 | 34 | 4 | 36 | 26 | 39 |
| Total | 200 | 200 | 200 | 200 | 200 | 200 |

TABLE 6

POINT COUNT DATA ON DETRITAL GRAINS (EXCLUDING CEMENT AND VOID COUNTS), NORMALIZED TO 100 PERCENT

| Percentage of Grain Type | Sample Number 1a | 1b | 2a | 2b | 3a | 3b | Average Composition Concretion | Sand |
|---|---|---|---|---|---|---|---|---|
| Feldspars | 17% | 20% | 31% | 28% | 37% | 39% | 28% | 29% |
| Quartz | 35 | 42 | 22 | 25 | 32 | 26 | 30 | 31 |
| Detrital carbonate | 10 | 10 | 4 | 4 | 6 | 4 | 7 | 6 |
| Rock fragments | 24 | 13 | 29 | 25 | 12 | 20 | 22 | 19 |
| Chert | 8 | 9 | 1 | 5 | 5 | 6 | 5 | 7 |
| Opaques + iron oxides | 6 | 6 | 13 | 13 | 8 | 5 | 8 | 8 |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

TABLE 7

POINT COUNT DATA ON CEMENT AND VOIDS (EXCLUDING DETRITAL GRAINS), NORMALIZED TO 100 PERCENT

| | | Sample Number | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Percentage Porosity Sand | 31 % | 19 % | 37.5% |
| Percentage Porosity Concretion | 38.5% | 43.5% | 49.5% |

TABLE 8

POINT COUNT DATA ON PLATY GRAINS

| Sample Number | Number of Platy Grains Counted | Number of Platy Grains Deformed | Percentage of Platy Grains Deformed |
|---|---|---|---|
| 1a | 20 | 9 | 45% |
| 1b | 20 | 10 | 50 |
| 2a | 20 | 8 | 40 |
| 2b | 15 | 14 | 93 |
| 3a | 21 | 8 | 38 |
| 3b | 18 | 13 | 72 |

# APPENDIX D

## MEASURED SECTIONS OF BULLION CREEK AND SLOPE FORMATIONS

## Measured Sections of Bullion Creek and Slope Formations

This appendix is a description of the measured lithologic sections. Seven of the measured sections are numbered (1 through 7); these sections were used to construct the cross section (Figure 5). All others are listed by their legal description. Elevations were determined from USGS topographic quadrangle maps (7.5 minute series) with a ten-foot contour interval. Therefore, each elevation has a precision of plus or minus five feet. In all cases, the thickness of the section measured is also the thickness of the outcrop. The scale of the diagrammatic sections is 20 mm to 1 metre, or 1 inch to about 4.5 feet. Lithologic symbols used are listed on the following page. All colors are those of the fresh lithology.

LITHOLOGIC SYMBOLS

| | |
|---|---|
| Sand or sandstone, massive | Clay |
| Sand or sandstone with large-scale cross-bedding | Silty clay |
| Sand or sandstone with small-scale cross-bedding | Lignite |
| Sand or sandstone with plane bedding | Carbonaceous clay |
| Sand or sandstone with contorted bedding | Silcrete |
| Sandstone with horizontal jointing | Plant fragments |
| Sandstone with concentric banding | Iron oxide concretions |
| Sandstone with radial jointing | Gypsum crystals |
| Conglomerate with sand matrix | Concealed |
| Silt | |

Measured section 1

Composite section; Bullion Creek Formation

Location: Lower 10.0 metres: T.130N., R.98W., sec. 15, NE¼, NW¼; section measured on west face of low hillside, 1/2 mile south, 1/2 mile east of Rose Hill Cemetery, at abandoned lignite mine. Upper 9.85 metres: T.130N., R.98W., sec. 3, NW¼, SW¼; section measured on roadcut, west side, on north-south blacktop road, 1/4 mile north of Routes 12 and 22.

Elevation at top of section: 2880 feet.

Thickness: 19.85 metres (65 feet).

Lignite; brown; highly weathered; oxidized at base; 0.35 m.

Clay; silty; light gray; contains laminae of light brown silt, very fine sand; contains iron oxide concretions (2-5 cm.) and plant fragments; 0.7 m.

Silt and very fine sand; light gray to light brown; massive; 0.45 m.

Clay; silty; light gray to gray; 0.65 m.

Silt and very fine sand; light gray; massive; 0.45 m.

Clay, light gray; and silt, light brown; interbedded (.2-1 cm. laminae); contains plant fragments, iron oxide concretions; 0.4 m.

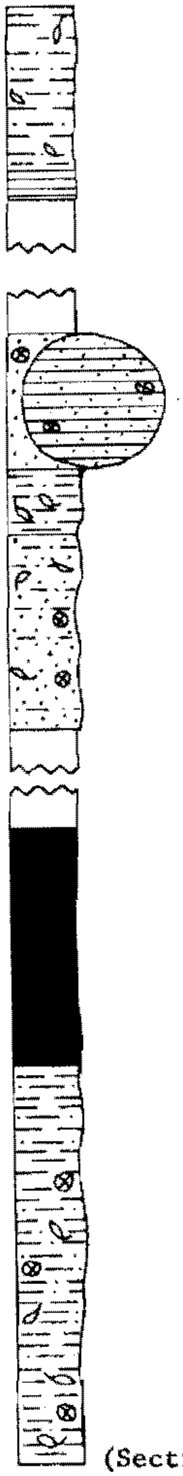
Clay; slightly silty; light gray to gray; contains plant fragments and selenite crystals; 2.9 m.

Horizon of iron oxide concretions; subspherically shaped (3-5 cm.); 0.15 m.

Clay; slightly silty; light gray to grayish brown; contains plant fragments; 2.5 m.

(Section continued on next page.)

Measured section 1 (continued)



Clay; silty; light gray to light brown; contains plant fragments; 1.1 m.

Carbonaceous clay; silty; dark brown; 0.2 m.

Concealed; 7.6 m.

Calcareous sandstone; elongate concretionary form; very fine to fine; light gray; contains iron oxide concretions (.5-2 cm.); plane-bedded; encased in massive, light gray, very fine to fine sand; 0.9 m.

Clay; silty; light gray to gray; contains plant fragments; 0.45 m.

Sand; very fine to fine; and silt; light gray; laminated with brown, organic material; contains iron oxide concretions (2-6 cm.); 1.3 m.

Concealed; 1.1 m.

Lignite; black; reddish weathered color in places; 1.6 m.

Clay; silty; light gray; contains plant fragments, iron oxide concretions (2-6 cm.); 2.7 m.

(Section continued on next page.)

Measured section 1 (continued)

Sand, very fine; and silt; light gray; thinly laminated with organic material; 0.25 m.

Horizon of iron oxide concretions; subspherically shaped (1-5 cm.); 0.1 m.

Clay; silty; light gray; contains plant fragments, iron oxide concretions (1-5 cm.); 0.85 m.

Lignite; black; 0.4 m.

(Base of section)

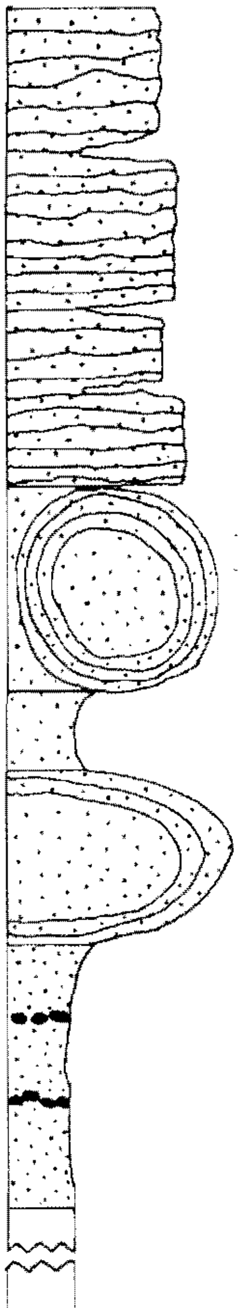
Measured section 2

Composite section; Bullion Creek and Slope Formations

Location: Lower 9.75 metres: T.129N., R.97W., sec. 22, NE¼, NW¼; section measured on west side of small knoll, just south of east-west section line road. Upper 23.5 metres: T.129N., R.97W., sec. 15, SE¼, SW¼; section measured on south side of large, sandstone-capped butte, 1/4 mile north of same road.

Elevation at top of section: 2950 feet.

Thickness: 33.25 metres (109 feet).



Calcareous sandstone; very fine to medium; pale yellow to light gray; massive; horizontally jointed; 3.2 m.

Calcareous sandstone; elongate concretionary form; very fine to medium; pale yellow; concentrically banded; massive; concretion encased in yellow, very fine to medium sand; 1.35 m.

Sand; very fine to medium; yellow; massive; 0.5 m.

Calcareous sandstone; concretionary form; very fine to medium; pale yellow; concentrically banded; massive; 1.2 m.

Sand; very fine to medium; pale yellow to light gray; contains layers of light gray claystone and siltstone clasts (.5-3 cm.); massive; 1.8 m.

Concealed; 1.3 m.

(Section continued on next page.)

Measured section 2 (continued)

Sand; very fine to medium; pale yellow to light gray; massive; 2.35 m.

Concealed; 3.6 m.

Clay; silty; light gray; contains plant fragments; 0.9 m.

Concealed; 1.05 m.

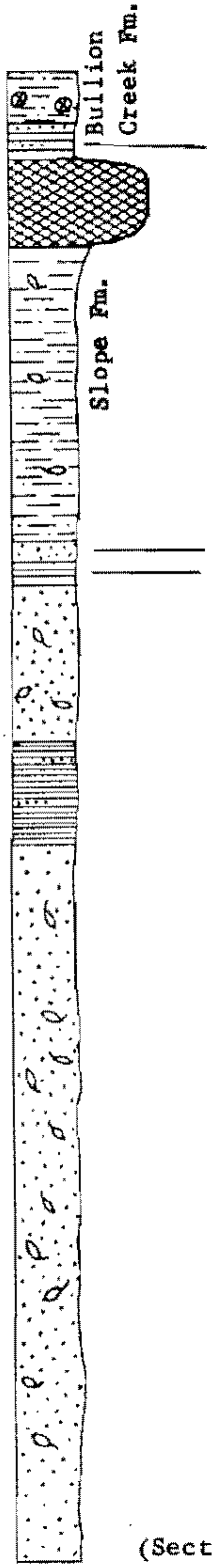
Lignite; slightly silty; 0.4 m.

Silt; clayey; light gray to light brown; contains plant fragments; 2.15 m.

Clay; silty; light gray to light brown; contains plant fragments; 2.5 m.

(Section continued on next page.)

Measured section 2 (continued)




Silt; light brown; contains subspherical iron oxide concretions (2-3 cm.); 0.35 m.

Carbonaceous clay; dark brown; contains laminae of very fine, light brown sand; 0.25 m.

Silcrete; white to light gray; contains plant molds; 0.6 m.

Clay; silty; light gray; contains plant fragments; 2.05 m.

Sand; very fine to fine; light gray; massive; 0.15 m.

Carbonaceous clay; sandy; dark brown; 0.15 m.

Sand; very fine to fine; light gray; contains plant fragments in thin laminae; 1.1 m.

Carbonaceous clay; dark brown; contains thin laminae of very fine sand; 0.7 m.

Sand; very fine to fine; light gray to light brown; contains plant fragments in thin laminae; 5.0 m.

(Section continued on next page.)

Measured section 2 (continued)

Clay; silty; light gray to light brown; contains plant fragments; 1.65 m.

Silt; light brown; contains plant fragments, iron oxide concretions (2-3 cm.); 0.35 m.

Sand; very fine to fine; light brown; contains thin laminae of carbonaceous material; 0.25 m.

(Base of section)

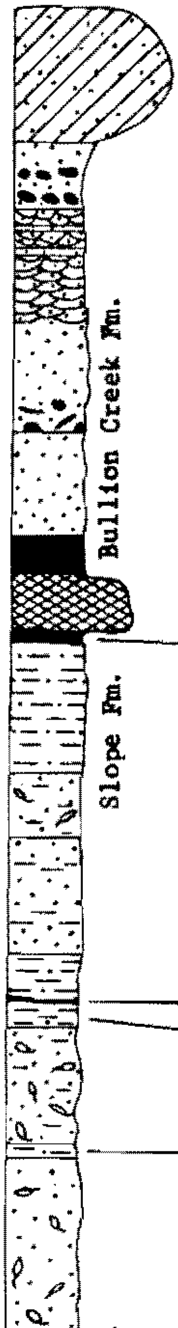
Measured section 3

Bullion Creek and Slope Formations

Location: T.129N., R.96W., sec. 17, SE¼, NE¼. Section measured on west side of small knoll, just west of ungraded, north-south dirt road.

Elevation at top of section: 2830 feet.

Thickness: 13.0 metres (42 feet).




Calcareous sandstone; elongate concretionary form; very fine to medium; light gray; large-scale cross-bedded; 0.9 m.

Sand; very fine to medium; light gray; contains light gray claystone, siltstone clasts (1-5 cm.); massive; 0.45 m.

Sand; very fine to fine; light gray; small-scale cross-bedded; plane-bedded in places; 0.75 m.

Sand; very fine to medium; light gray; contains light gray claystone clasts and bladed lignite fragments near base (1-5 cm.); massive; 0.75 m.

Sand; very fine to fine; light gray; massive; 0.7 m.

Lignite; dark brown to black; oxidized at top; 0.25 m.

Silcrete; very light gray to white; numerous plant molds; 0.4 m.

Lignite; black; 0.05 m.

Clay; silty; light gray; contains plant fragments; 0.9 m.

Sand; very fine; and silt; light gray; thinly laminated; contains plant fragments; 0.4 m.

Sand; very fine; and silt; grayish brown; interbedded with clay, dark grayish brown; 0.9 m.

Clay; silty; gray; massive; 0.2 m.

Lignite; black; 0.05 m.

Clay; silty; gray; massive; 0.15 m.

Sand; very fine to fine; clayey; light gray to white; contains plant fragments; massive; 0.8 m.

Clay; silty; light gray; massive; 0.1 m.

Sand; very fine to medium; light gray to white; contains laminae of plant material; 1.2 m.

(Section continued on next page.)

Measured section 3 (continued)

Clay; silty; lignitic; dark brown; contains thin laminae (1-3 cm.) of very fine to fine, light gray sand; 1.35 m.

Clay; light gray; massive; 0.3 m.

Sand; very fine to medium; light gray to light brown; contains discontinuous layers of lignitic material; 0.35 m.

Concealed; 1.45 m.

Clay; gray; massive; 0.1 m.

Sand; very fine to fine; light gray to light brown; contains thin bands (2-3 cm.) of lignitic material; 0.25 m.

(Base of section)

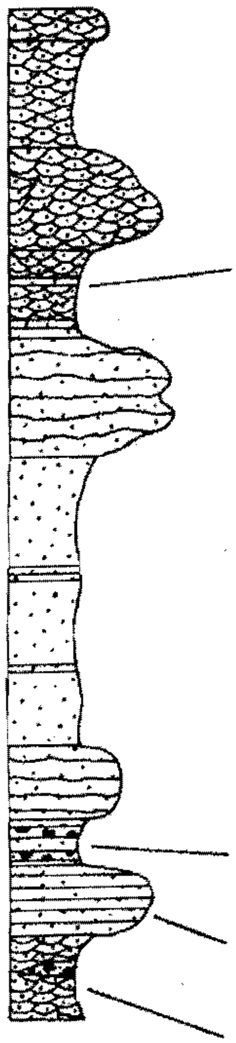
Measured section 4

Composite section; Bullion Creek and Slope Formations

Location: Lowermost 4.8 metres: T.129N., R.96W., sec. 1, NW¼,NE¼; section measured on south side of low hill on which wind pump is located. Middle 11.6 metres: T.129N., R.96W., sec. 12, NW¼, NW¼; section measured on south side of hill in clay pit in maintainance yard of Adams Co. Highway Dept. Uppermost 15.3 metres: T.130N., R.96W., sec. 34, SE , SE¼; section measured on southwest face of small butte, 1½ mile northwest of Hettinger Municipal Airport.

Elevation at top of section: 2860 feet.

Thickness: 31.7 metres (104 feet).



Calcareous sandstone; laterally continuous concretionary ledge; very fine to fine; light gray; small-scale cross-bedded; 0.2 m.

Sand; very fine to fine; pale yellow; small-scale cross-bedded; 0.7 m.

Calcareous sandstone; concretionary form; very fine to fine; pale yellow to light gray; small-scale cross-bedded; 0.7 m.

Sand; very fine to fine; pale yellow; small-scale cross-bedded; plane-bedded in places; 0.6 m.

Calcareous sandstone; elongate concretionary form; very fine to fine; pale yellow to light gray; massive; horizontally jointed; 0.8 m.

Sand; very fine to fine; pale yellow; massive; plane-bedded in places; 1.9 m.

Calcareous sandstone; laterally continuous concretionary ledge; very fine to medium; pale yellow to light gray; massive; horizontally jointed; 0.5 m.

Sand; very fine to medium; pale yellow; contains light gray claystone, siltstone clasts (.5-5 cm.) on bedding planes; plane-bedded; 0.3 m.

Calcareous sandstone; laterally continuous concretionary ledge; very fine to fine; pale yellow; plane-bedded; 0.5 m.

Sand; very fine to fine; pale yellow; contains 15 cm. lens of conglomerate with light gray claystone, siltstone (.5-3 cm.) clasts; small-scale cross-bedded; 0.55 m.

(Section continued on next page.)

Concealed; 1.05 m.

Sand; very fine to fine; pale yellow to light gray; massive; 0.45 m.

Concealed; 3.5 m.

Clay; silty; light gray to light brown; contains thin (5-8 cm.) bands of lignitic material; 1.4 m.

Carbonaceous clay; dark brown to dark gray; 0.4 m.

Concealed; 0.7 m.

Silt; clayey; pale yellow to light brown; 1.1 m.

Concealed; 0.5 m.

Clay; silty; light brown to light gray; laminated; 0.45 m.

Concealed; 0.45 m.

Clay; silty; gray; laminated; 0.15 m.
Lignite; black; 0.3 m.

Clay; silty; light brown to light gray; contains plant fragments; 1.35 m.

Concealed; 0.55 m.

Silt; light brown; 0.2 m.

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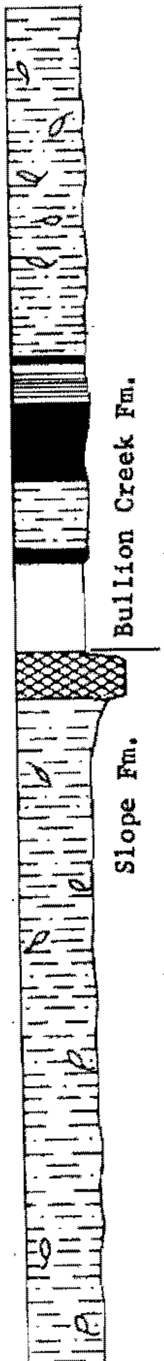



Clay; silty; light gray to light brown; thinly laminated; contains plant fragments; 2.35 m.

Lignite; black; oxidized in places; contains carbonaceous clay near top; 0.85 m.

Clay; silty; light gray; 0.45 m.
Lignite; black; 0.1 m.
Concealed; 0.6 m.
Silcrete; light gray to white; contains plant molds; 0.3 m.

Clay; silty; light to medium gray; contains plant fragments; 4.5 m.

(Base of section)

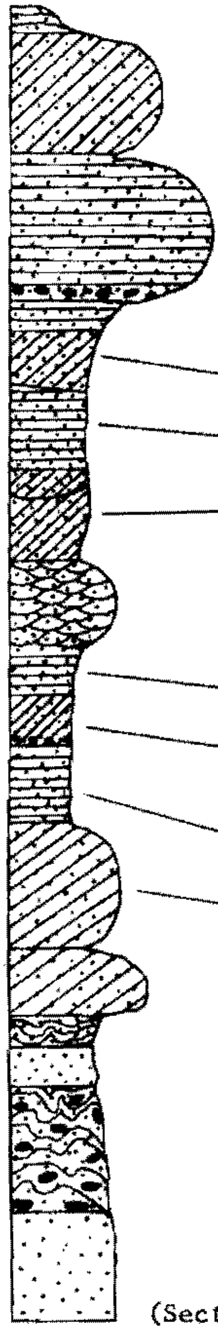
Measured section 5

Bullion Creek Formation

Location: T.129N., R.95W., sec. 21, SE¼, SW¼. Section measured on western end of narrow, east-west-oriented butte, about 1/2 mile south of Flat Creek.

Elevation at top of section: 2785 feet.

Thickness: 16.2 metres (53 feet).



Calcareous sandstone; elongate concretionary form; very fine to medium; pale yellow; large-scale cross-bedded; upper few cm. are horizontally jointed; 1.0 m.

Calcareous sandstone; elongate concretion form; very fine to medium; pale yellow; contains light gray claystone clasts (.5-2 cm.) at base; plane-bedded; 1.0 m.

Sand; very fine to medium; pale yellow; plane-bedded; 0.2 m.

Sand; very fine to medium; pale yellow; large-scale cross-bedded; 0.45 m.

Sand; very fine to medium; pale yellow; plane-bedded; 0.5 m.

Sand; very fine to medium; pale yellow; large-scale cross-bedded; 0.6 m.

Calcareous sandstone; concretionary form; very fine to medium; pale yellow; small-scale cross-bedded; 0.6 m.

Sand; very fine to medium; pale yellow; plane-bedded; 0.3 m.

Sand; very fine to medium; pale yellow; contains light gray claystone clasts (.5-2 cm.) at base; large-scale cross-bedded; 0.35 m.

Sand; very fine to medium; pale yellow; plane-bedded; 0.5 m.

Calcareous sandstone; very fine to medium; pale yellow; large-scale cross-bedded; 0.8 m.

Calcareous sandstone; elongate concretionary form; very fine to medium; pale yellow; large-scale cross-bedded; 0.45 m.

Calcareous sandstone; very fine to medium; pale yellow to light gray; contains conglomerate (light gray claystone clasts, .5-5 cm.) and contorted bedding in middle and near top; otherwise, massive; 2.1 m.

(Section continued on next page.)

Measured section 5 (continued)

Sand; very fine to medium; pale yellow; massive; 2.0 m.

Sand; very fine to fine; light gray to pale yellow; contains bands (2-20 cm.) of light gray clay and silt; 3.5 m.

Concealed; 0.9 m.

Sand; very fine to fine; light gray; contains bands of iron oxide staining; massive; 0.9 m.

(Base of section)

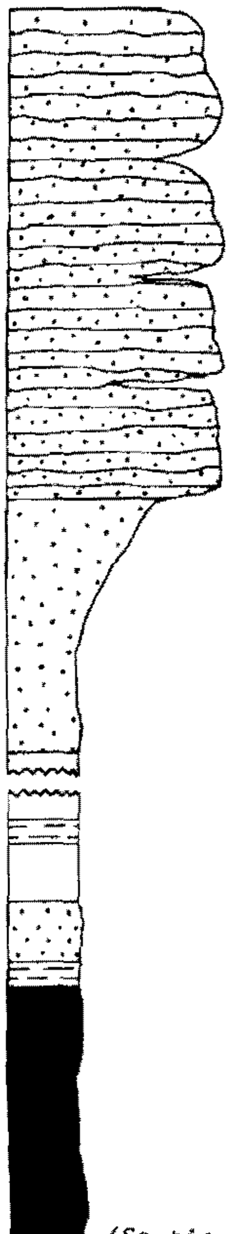
Measured section 6

Composite section, Bullion Creek and Slope Formations

Location: Lower 3.6 metres: T.131N., R.93W., sec. 34, SE¼, NW¼. Section measured on east face of small, white knoll. Upper 8.45 metres: T.131N., R.93W., sec.34, NW¼, SE¼. Section measured on east face of low, sandstone-capped hill, about 300 yards northwest of previous white knoll.

Elevation at top of section: 2570 feet.

Thickness: 12 metres (40 feet).



Calcareous sandstone; elongate concretionary form; very fine to fine; pale yellow to pale brown; horizontally jointed; 1.0 m.

Calcareous sandstone; forms laterally continuous ledge; very fine to fine; pale yellow to pale brown; plane-bedded; horizontally jointed; 2.3 m.

Sand; very fine to medium; light gray; massive; 1.65 m.

Concealed; 0.65 m.

Clay; gray; 0.15 m.

Concealed; black, lignitic soil; 0.4 m.

Sand; very fine to fine; light gray; massive; 0.4 m.

Clay; gray; 0.15 m.

Lignite; black; contains red bands (1-5 cm.) of oxidized material; 1.75 m.

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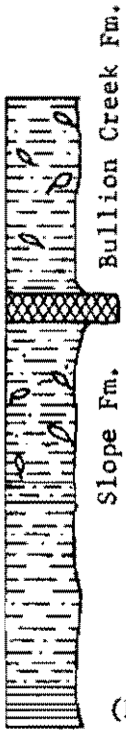
Measured section 6 (continued)




Clay; silty; gray to brown; contains plant fragments; 1.3 m.

Silcrete; white to light gray; contains plant fragment molds; 0.2 m.

Clay; silty and sandy; light gray; contains plant fragments; contains red-yellow bands (2-3 cm.) of oxidized material; 1.05 m.

Silt; reddish-brown, oxidized color; contains black, carbonaceous fragments; 0.15 m.

Clay; silty; gray to dark gray; becomes dark brown and carbonaceous near base; 1.5 m.

(Base of section)

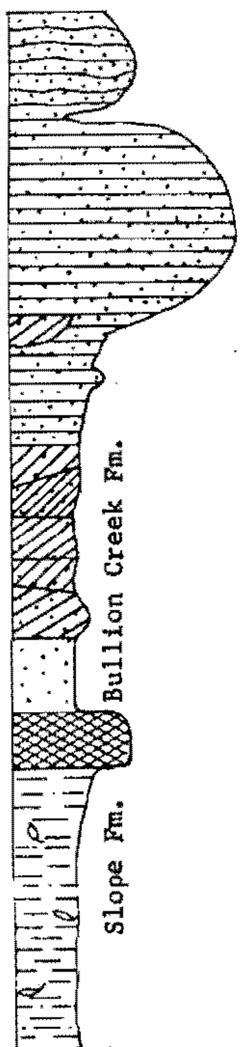
Measured section 7

Composite section; Bullion Creek and Slope Formations

Location: Lowermost 12.25 metres: T.129N., R.92W., sec. 11, SW¼, NW¼; section measured on south side of southern-most small, rocky knoll, North Lemmon Lake State Game Management Area. Middle 5.15 metres: T.129N., R.92W., sec. 21, NE¼, NE¼; section measured on roadcut, south side, on east-west dirt road several hundred yards west of North Lemmon District school house. Uppermost 4.7 metres: T.129N., R.92W., sec. 16, NW¼,NE¼; section measured on east side of north-trending gully, 1.5 miles west and .5 miles south of North Lemmon Lake State Game Management Area.

Elevation at top of section: 2610 feet.

Thickness: 22.1 metres (72.5 feet).




Calcareous sandstone; elongate concretionary form; very fine to fine; pale yellow to light brown; massive; horizontally jointed; 0.7 m.

Calcareous sandstone; elongate concretionary form; very fine to fine; pale yellow to light brown; plane-bedded; large-scale cross-bedded near base; 1.5 m.

Sand; locally cemented with calcite; very fine to fine; pale yellow; plane-bedded; 0.7 m.

Sand; locally cemented with calcite; very fine to medium; pale yellow; large-scale cross-bedded; 1.3 m.

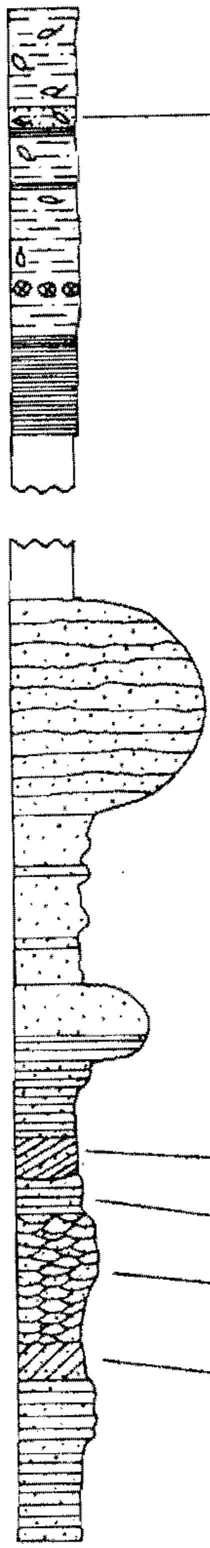
Sand; very fine to medium; pale yellow to light gray; massive; 0.5 m.

Silcrete; light gray to white; contains plant molds; 0.35 m.

Clay; silty; light gray to gray; contains plant fragments; 1.95 m.

(Section continued on next page.)

Measured section 7 (continued)



Clay; light gray; interbedded with silt, light brown; contains plant fragments; 0.65 m.

Sand; very fine to fine; and silt; light brown; contains disseminated plant material; massive; 0.15 m.

Clay; silty; gray; contains black, carbonaceous clay bands near top, iron oxide concretions near base, plant fragments throughout; 1.15 m.

Carbonaceous clay; dark brown; 0.65 m.

Concealed; 2.7 m.

Calcareous sandstone; elongate concretionary form; very fine to medium; light gray; massive; horizontally jointed; 1.4 m.

Sand; some horizons are calcite-cemented; very fine to fine; pale yellow; massive; plane-bedded in part.

Calcareous sandstone; elongate concretionary form; very fine to medium; pale yellow to light gray; massive; plane-bedded near base; 0.55 m.

Sand; very fine to medium; pale yellow; plane-bedded; 0.5 m.

Sand; very fine to medium; pale yellow; large-scale cross-bedded; 0.25 m.

Sand; very fine to medium; pale yellow; plane-bedded; 0.25 m.

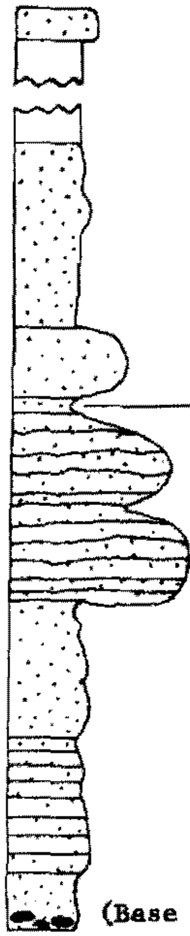
Sand; upper part is weakly cemented with iron oxide; very fine to medium; reddish brown and pale yellow to light gray; small-scale cross-bedded; 0.9 m.

Sand; weakly cemented with iron oxide; very fine to medium; reddish brown and pale yellow; large-scale cross-bedded; 0.25 m.

Sand; some horizons weakly cemented with iron oxide; very fine to medium; reddish brown and pale yellow; plane-bedded; 1.1 m.

(Section continued on next page.)

Measured section 7 (continued)



Sand; weakly cemented with iron oxide; very fine to medium; reddish brown; massive; 0.2 m.

Concealed; 0.9 m.

Sand; weakly cemented with calcite; very fine to medium; pale yellow to light gray; massive; 1.25 m.

Calcareous sandstone; concretionary form; very fine to medium; light brown; massive; 0.45 m.

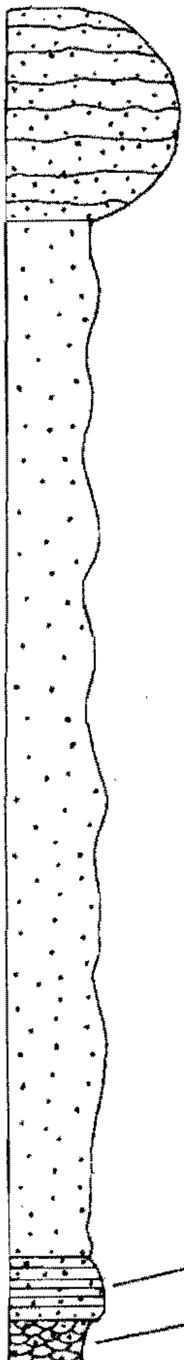
Sand; very fine to medium; pale yellow; massive; 0.1 m.

Calcareous sandstone; elongate concretionary form; very fine to medium; pale yellow to light brown; massive; horizontally jointed; 1.3 m.

Sand; weakly cemented with iron oxide; very fine to medium; reddish brown; contains light gray claystone clasts (.5-2 cm.) near base; massive; plane-bedded in middle; 2.2 m.

(Base of section)

Bullion Creek Formation
Location: T.23N., R.14E., sec. 20, NW¼, SW¼; Perkins Co., S.D. Section measured on east side of steep, north-south ravine, about 1/4 mile south of state line.
Elevation at top of section: 2680 feet.
Thickness: 23 metres (76 feet).



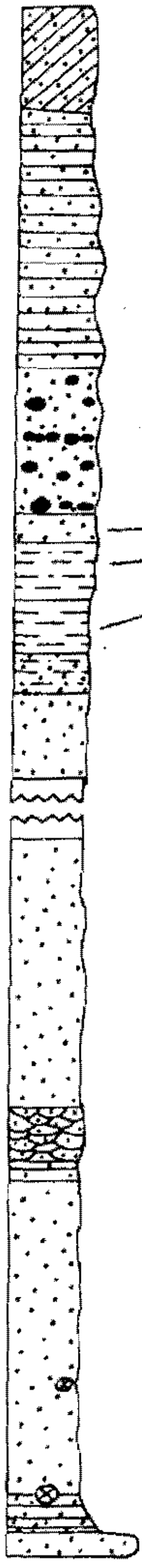
Calcareous sandstone; elongate concretion form; sample 2a collected here; very fine to medium; brownish yellow; massive; irregular, horizontal jointing; 1.4 m.

Sand; sample 2b collected at top; very fine to medium; yellow; some horizons cemented with iron oxide (10-20 cm. thick); massive; 7.0 m.

Sandstone; weakly cemented with iron oxide; very fine to medium; brownish red; plane-bedded; 0.4 m.

Sand; very fine to fine; yellow; small-scale cross-bedded; 0.3 m.

(Section continued on next page.)



Sand; very fine to medium; yellow; large-scale cross-bedded; 0.7 m.

Sand; very fine to medium; yellow to light gray; some horizons are iron oxide-cemented; plane-bedded; 1.7 m.

Sand; very fine to medium; yellow; contains light gray claystone, siltstone clasts (2-8 cm.); massive; 1.0 m.

Sand; very fine to medium; yellow; massive; 0.2 m.

Clay; silty; grayish brown; thinly laminated; 0.4 m.

Clay; alternating bands of maroon and gray; 0.35 m.

Sand; very fine; silty; yellow; thinly laminated; 0.25 m.

Sand; very fine to medium; yellow; massive; 0.6 m.

Concealed; 0.6 m.

Sand; very fine to medium; yellowish gray; massive; 1.8 m.

Sand; very fine to medium; yellowish gray; small-scale cross-bedded; 0.35 m.

Sand; very fine to medium; yellow; plane-bedded in places; contains scattered iron oxide concretions (5-10 cm.); 2.55 m.

Sandstone; weakly cemented with iron oxide; very fine to medium; brownish red; 0.15 m.

(Section continued on next page.)

Sand; cemented with iron oxide in places; very fine to medium; yellow to light gray, reddish brown in places; massive; 2.3 m.

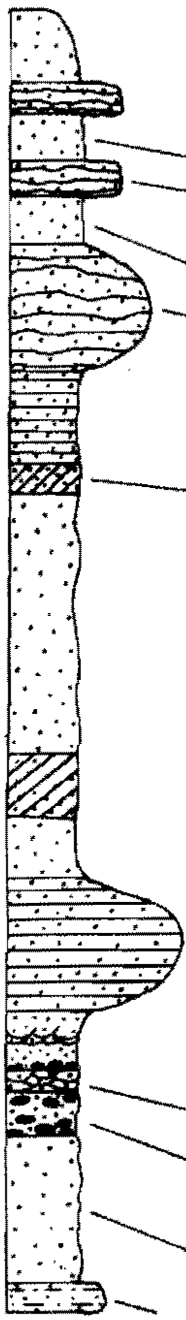
Sand; cemented with iron oxide near top; very fine to medium; yellow and reddish brown; plane-bedded; 0.6 m.

Sand; very fine to medium; yellow; contains light gray clay clasts (.5-2 cm.); large-scale cross-bedded; 0.1 m.

Sand; very fine to medium; yellow; plane-bedded; 0.3 m.

(Base of section)

Bullion Creek Formation
Location: T.129N., R.94W., sec. 30, NE¼, SW¼. Section measured on southeast face of sandstone-capped butte, about 1/2 mile southwest of Haynes, N.D. and 1/4 mile south of Flat Creek.
Elevation at top of section: 2710 feet.
Thickness: 13 metres (43 feet).



Sand; very fine to fine; pale yellow; massive; 0.5 m.

Calcareous sandstone; forms laterally continuous ledge; very fine to fine; pale yellow to pale brown; massive; horizontally jointed; 0.2 m.

Sand; very fine to fine; pale yellow; massive; 0.3 m.

Calcareous sandstone; forms laterally continuous ledge; very fine to fine; pale yellow to pale brown; massive; horizontally jointed; 0.25 m.

Sand; very fine to fine; pale yellow; massive; 0.35 m.

Calcareous sandstone; elongate concretionary form; very fine to fine; pale yellow to pale brown; massive; horizontally jointed; 0.9 m.

Sand; very fine to medium; pale yellow; plane-bedded; 0.6 m.

Sand; very fine to medium; pale yellow; large-scale cross-bedded; 0.2 m.

Sand; very fine to medium; light gray to pale yellow; massive; 1.75 m.

Sand; very fine to medium; light gray to pale yellow; large-scale cross-bedded; 0.45 m.

Sand; very fine to fine; light gray; massive; 0.4 m.

Calcareous sandstone; elongate concretionary form; very fine to fine; light gray; plane-bedded; 0.9 m.

Sand; very fine to fine; light gray; contains light gray claystone, siltstone clasts (.5-5 cm.) at base; small-scale cross-bedded in places; 0.4 m.

Sand; very fine to fine; light gray; small-scale cross-bedded; 0.15 m.

Sand; very fine to coarse; light gray; contains light gray claystone, siltstone clasts (.5-8 cm.); massive; 0.3 m.

Sand; very fine to medium; pale yellow to light gray; massive; 1.05 m.

Calcareous sandstone; very fine; silty; light gray; iron oxide-stained; massive; 0.2 m.

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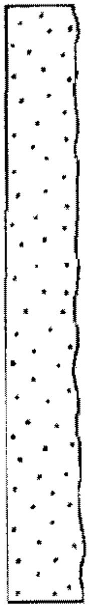
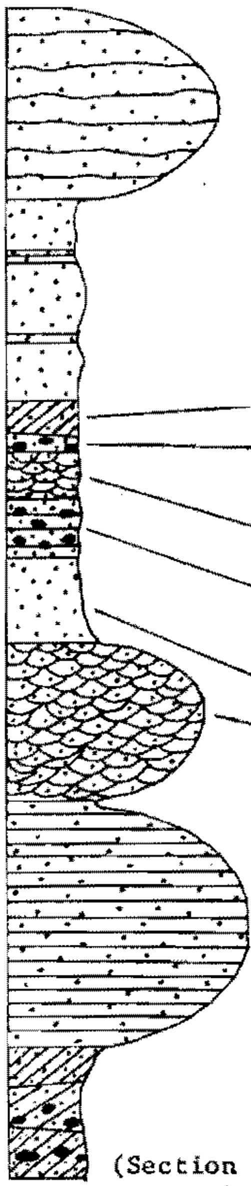


Sand; very fine to medium; pale yellow to light gray; massive; 4.0 m.

(Base of section)

Bullion Creek Formation
Location: T.129N., R.94W., sec. 30, SE¼, NE¼. Section measured on west face of large cliff, about 1/2 mile southwest of Haynes, N.D.
Elevation at top of section: 2700 feet.
Thickness: 10.5 metres (34 feet).



Calcareous sandstone; elongate concretionary form; very fine to fine; pale yellow to light gray; horizontally jointed; 1.3 m.

Sand; very fine to medium; yellow and reddish brown; some horizons are iron oxide-cemented; massive; plane-bedded in parts; 1.35 m.

Sand; very fine to medium; yellow; large-scale cross-bedded; 0.25 m.

Sand; very fine to medium; yellow; contains light gray claystone clasts (1-3 cm.); plane-bedded; 0.1 m.

Sand; very fine to medium; yellow to light gray; small-scale cross-bedded; 0.3 m.

Sand; very fine to medium; yellow to light gray; contains light gray claystone clasts (1-5 cm.); plane-bedded; 0.4 m.

Sand; very fine to medium; yellow; massive; 0.55 m.

Calcareous sandstone; elongate concretionary form; very fine to fine; pale yellow; small-scale cross-bedded; 1.05 m.

Calcareous sandstone; elongate concretionary form; very fine to fine; pale yellow; plane-bedded; 1.7 m.

Sand; very fine to medium; yellow; contains light gray claystone clasts (1-5 cm.); large-scale cross-bedded; 0.9 m.

(Section continued on next page.)

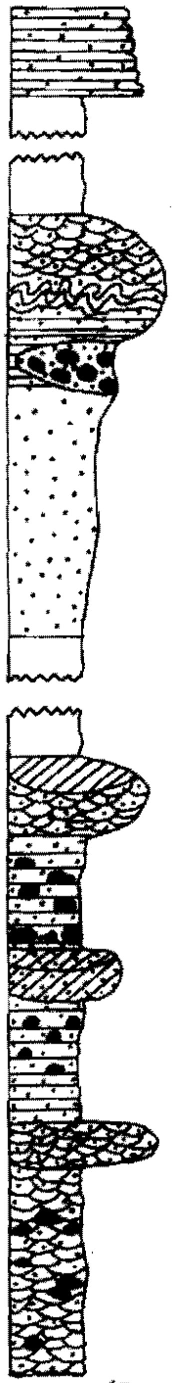
Sand; very fine to medium; yellow; lower portion contains light gray claystone, siltstone clasts (1-5 cm.) on bedding planes; massive near top; 0.8 m.

Sand; very fine to medium; yellow; light gray claystone, siltstone clasts (1-5 cm.) near base; massive; 0.75 m.

Sand; very fine to medium; yellow; plane-bedded; 1.0 m.

(Base of section)

Bullion Creek Formation
Location: T.129N., R.94W., sec. 33, NE¼, SW¼. Section measured on northeast side of sandstone-capped butte, about 1/2 mile south of Flat Creek.
Elevation at top of section: 2570 feet.
Thickness: 19.0 metres (62 feet).



Calcareous sandstone; very fine to fine; pale yellow; plane-bedded; horizontally jointed; 0.6 m.

Concealed; 5.4 m.

Calcareous sandstone; elongate concretionary form; very fine to fine; pale yellow; small-scale cross-bedded; contains contorted bedding and plane bedding in places; 0.85 m.

Conglomerate; lens-shaped body; light gray siltstone clasts (1-15 cm.); matrix is pale yellow, very fine to medium sand; 0.45 m.

Sand; very fine to medium; pale yellow; massive; 1.6 m.

Concealed; 4.5 m.

Calcareous sandstone; concretionary form; very fine to medium; pale yellow to light gray; large- and small-scale cross-bedded; 0.55 m.

Sand; very fine to medium; pale yellow; contains layers of light gray claystone, siltstone clasts (4-8 cm.); plane-bedded; 0.8 m.

Calcareous sandstone; concretionary form; very fine to medium; pale yellow; large-scale cross-bedded; 0.35 m.

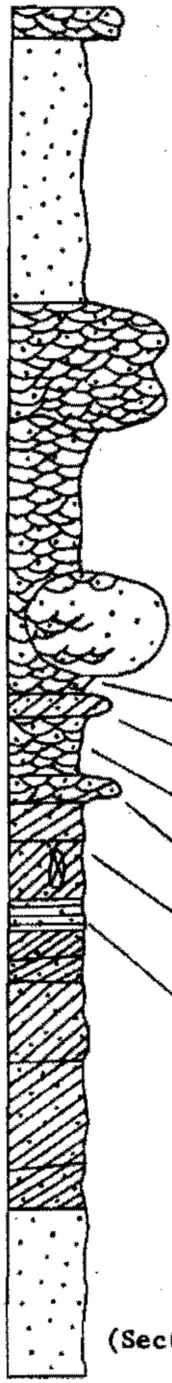
Sand; very fine to medium; pale yellow; contains layers of light gray claystone, siltstone clasts (2-10 cm.); plane-bedded; 0.8 m.

Calcareous sandstone; elongate concretionary form; very fine to medium; pale yellow; small-scale cross-bedded; 0.3 m.

Sand; very fine to medium; pale yellow to light brown; contains light gray siltstone clasts (1-5 cm.); small-scale cross-bedded; 1.4 m.

(Base of section).

Bullion Creek Formation
Location: T.129N., R.94W., sec. 36, NW¼, NW¼. Section measured on west face of sandstone-capped hill, about 1/3 mile north of railroad and 1/2 mile east of Highway 12.
Elevation at top of section: 2640 feet.
Thickness: 20.0 metres (66 feet).



Calcareous sandstone; forms laterally continuous ledge; very fine to fine; pale yellow; small-scale cross-bedded; 0.2 m.

Sand; very fine to fine; yellow; massive; 1.8 m.

Calcareous sandstone; elongate concretionary form; very fine to fine; pale yellow; small-scale cross-bedded; 0.8 m.

Sand; very fine to fine; yellow; small-scale cross-bedded; 0.95 m.

Calcareous sandstone; concretionary form; very fine to fine; pale yellow; massive with some small-scale cross-bedding; bedding continuous into surrounding sand; 0.7 m.

Sand; very fine to fine; yellow; small-scale cross-bedded; 0.1 m.

Sandstone; iron oxide-stained; very fine to fine; reddish brown; large-scale cross-bedded; 0.15.

Sand; very fine to fine; yellow; small-scale cross-bedded; 0.45 m.

Sandstone; iron oxide-stained; very fine to fine; reddish brown; small-scale cross-bedded; 0.15 m.

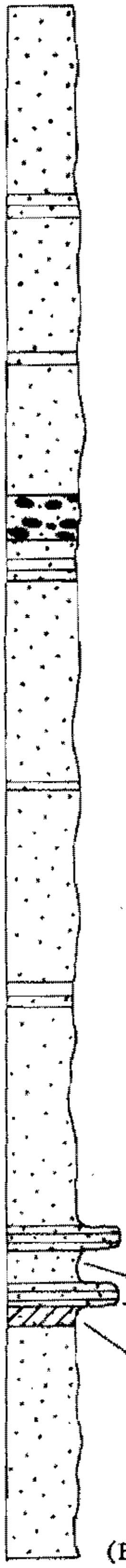
Sand; very fine to medium; yellow; large-scale cross-bedded; contains tube-like iron oxide concretions; 0.65 m.

Sand; very fine to medium; yellow; plane-bedded; 0.2 m.

Sand; very fine to medium; yellow; large-scale cross-bedded; 1.9 m.

Sand; very fine to medium; yellow; massive; 1.1 m.

(Section continued on next page.)



Sand; very fine to medium; yellow; massive; plane-bedded in places; 3.4 m.

Sand; very fine to medium; pale yellow; contains light gray claystone clasts (2-5 cm.); massive; 0.3 m.

Sand; very fine to medium; yellow; massive; plane-bedded in places; 4.85 m.

Sandstone; iron oxide-stained; very fine to medium; plane-bedded; 0.15 m.

Sand; very fine to medium; yellow; massive; 0.25 m.

Sandstone; iron oxide-stained; very fine to medium; brownish red; plane-bedded; 0.15 m.

Sand; very fine to medium; yellow; large-scale cross-bedded; 0.15 m.

Sand; very fine to medium; yellow; massive; 1.65 m.

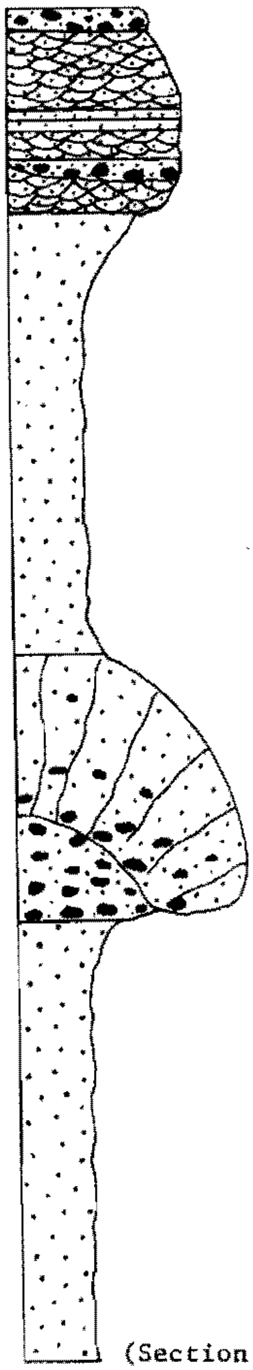
(Base of section)

Bullion Creek Formation

Location: T.129N., R.95W., sec. 20, SE¼, NE¼. Section measured on north side of hill, up the side of gully. Site is 3/4 miles east of north-south black top road which leads south out of Hettinger, N.D.

Elevation at top of section: 2800 feet.

Thickness: 30 metres (99 feet).



Conglomeratic, calcareous sandstone; very fine to medium: yellowish brown; contains light gray claystone, siltstone clasts (1-5 cm.); 0.15 m.

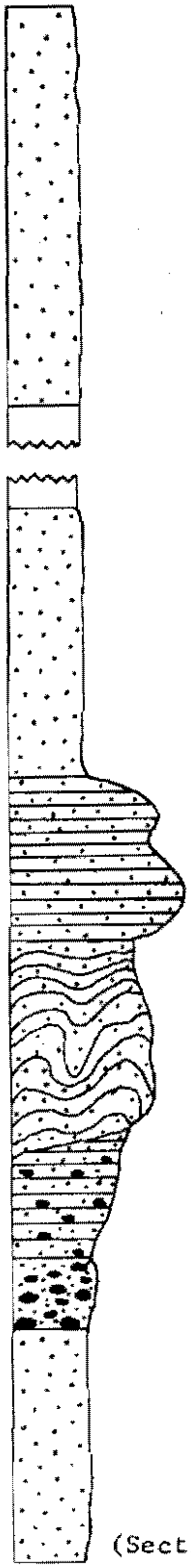
Calcareous sandstone; concretionary form; very fine to fine; yellowish brown; contains conglomeratic lens of light gray claystone, siltstone clasts (1-5 cm.) in very fine to medium sand matrix; 0.15 m.; sandstone is small-scale cross-bedded; plane-bedded in places; 1.2 m.

Sand; very fine to medium; light gray; massive; 2.7 m.

Conglomeratic, calcareous sandstone; elongate concretionary form; inner portion of concretion is uncemented; irregular transverse shape; very fine to medium; light brown to yellowish brown; contains contains light gray claystone, siltstone clasts (.5-8 cm.) that decrease in size and concentration upward; massive; contains radial jointing; 1.8 m.

Sand; very fine to medium; pale yellow to light gray; massive; stained with iron oxide along some horizons; 3.0 m.

(Section continued on next page.)



Sand; very fine to fine; pale yellow to light gray; massive; 2.7 m.

Concealed; 1.8 m.

Sand; very fine to fine; pale yellow to light brown; massive; 1.8 m.

Calcareous sandstone; elongate concretionary form; very fine to fine; pale yellow to light gray; plane-bedded; 1.1 m.

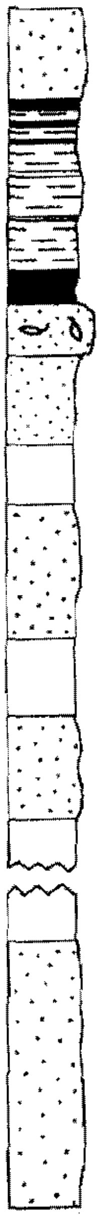
Calcareous sandstone; very fine to fine; light gray; contorted bedding; uneven lower contact; about 1.4 m.

Sand; very fine to medium; pale yellow to light brown; contains light gray claystone, siltstone clasts (.5-3 cm.) on bedding planes; plane-bedded; 0.85 m.

Conglomeratic sand; matrix is very fine to medium; light brown; clasts are light gray claystone, siltstone (.5-6 cm.); massive; 0.5 m.

Sand; very fine to medium; pale yellow; massive; 1.6 m.

(Section continued on next page.)



Sand; very fine to medium; pale yellow; massive; 0.6 m.

Lignite; black; powdery; contains bands (5 cm.) of gray clay; 0.3 m.

Clay; dark grayish brown; contains carbonaceous bands; 0.85 m.

Lignite; black; powdery; 0.2 m.

Sandstone; iron oxide cement; very fine to medium; contains plant fragments; massive; 0.35 m.

Sand; very fine to medium; pale yellow to light gray; massive; 0.6 m.

Concealed; 0.4 m.

Sand; very fine to medium; pale yellow; massive; 0.9 m.

Concealed; 0.5 m.

Sand; very fine to medium; pale yellow to light brown; massive; 0.7 m.

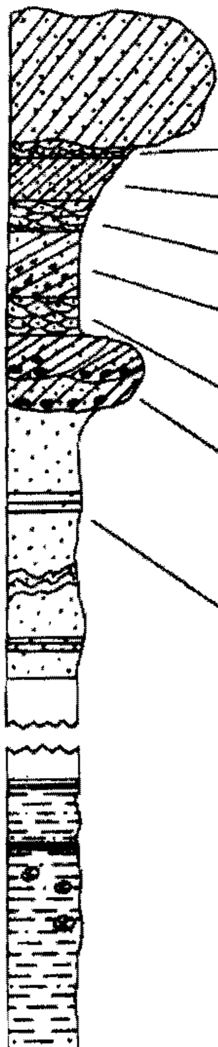
Concealed; 2.0 m.

Sand; very fine to fine; pale yellow to light gray; massive; 1.8 m.

(Base of section)

Bullion Creek Formation

Location: T.129N., R.95W., sec. 21, SE¼, SE¼. Section measured on south side of sandstone-capped butte, about 1/4 mile north of ungraded east-west dirt road and about 200 yards northwest of junction of north-south and east-west section fence lines.
Elevation at top of section: 2790 feet.
Thickness: 8.2 metres (27 feet).



Calcareous sandstone; elongate concretionary form; very fine to medium; pale yellow to brownish yellow; large-scale cross-bedded; 0.9 m.

Sand; very fine to fine; pale yellow; small-scale cross-bedded; 0.1 m.

Sand; very fine to medium; pale yellow; large-scale cross-bedded; 0.3 m.

Sand; very fine to fine; pale yellow; small-scale cross-bedded; 0.2 m.

Sand; very fine to medium; pale yellow; contains light gray claystone, siltstone clasts (.5-2 cm.) on foresets; large-scale cross-bedded; 0.45 m.

Sand; very fine to fine; pale yellow; small-scale cross-bedded; 0.25 m.

Calcareous sandstone; concretionary form; very fine to medium; pale yellow to light brownish gray; contains light gray claystone, siltstone clasts (.5-2 cm.) at bases of foresets; large-scale cross-bedded; 0.5 m.

Sand; very fine to medium; pale yellow to light gray; massive; plane-bedded and contorted bedding in places; 1.8 m.

Concealed; 1.7 m.

Clay; silty; brownish gray to gray; contains black, carbonaceous clay bands near top; yellow, highly weathered concretions (2-4 cm.) near middle; 1.8 m.

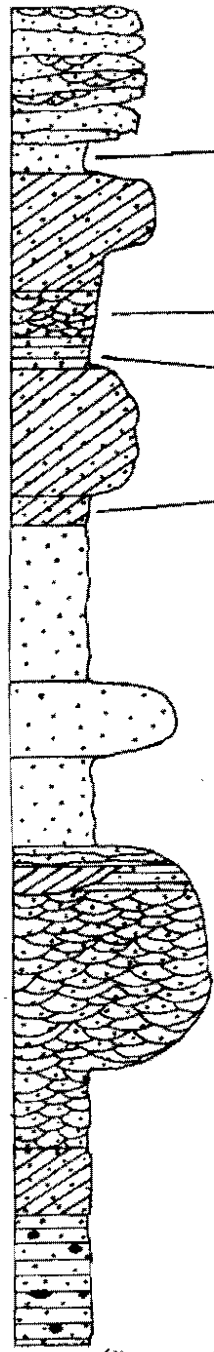
(Base of section)

Bullion Creek Formation

Location: T.129N., R.95W., sec. 25, NW¼, NW¼. Section measured on south side of sandstone-capped ridge, about 1/4 mile north of east-west dirt road.

Elevation at top of section: 2760 feet.

Thickness: 9.0 metres (29.5 feet).



Calcareous sandstone; elongate concretionary form; very fine to medium; light gray; small-scale cross-bedded; horizontally jointed; 0.9 m.

Sand; very fine to medium; pale yellow; massive; 0.2 m.

Calcareous sandstone; variably cemented; fine to coarse; pale yellow to light gray; contains white claystone clasts (1-2 cm.) on foresets; large-scale cross-bedded; 0.8 m.

Sand; very fine to fine; pale yellow; small-scale cross-bedded; 0.3 m.

Sand; very fine to fine; pale yellow; plane-bedded; 0.2 m.

Calcareous sandstone; concretionary form; very fine to fine; light gray; large-scale cross-bedded; 0.85 m.

Sand; very fine to medium; pale yellow; large-scale cross-bedded; 0.2 m.

Sand; very fine to fine; pale yellow; massive; 1.05 m.

Calcareous sandstone; elongate concretionary form; very fine to medium; light gray; massive; 0.5 m.

Sand; very fine to medium; pale yellow; massive; 0.6 m.

Calcareous sandstone; concretionary form; upper 0.55 m. is very fine to medium, light gray, large-scale cross-bedded, plane-bedded, and horizontally jointed; lower 1.2 m. is very fine to fine, light gray, small-scale cross-bedded; 1.5 m. (total thickness).

Sand; very fine to fine; pale yellow; small-scale cross-bedded; 0.55 m.

Sand; very fine to medium; pale yellow; large-scale cross-bedded; 0.45 m.

Sand; very fine to medium; pale yellow; contains scattered light gray claystone, siltstone clasts (1-3 cm.); plane-bedded; 0.9 m.

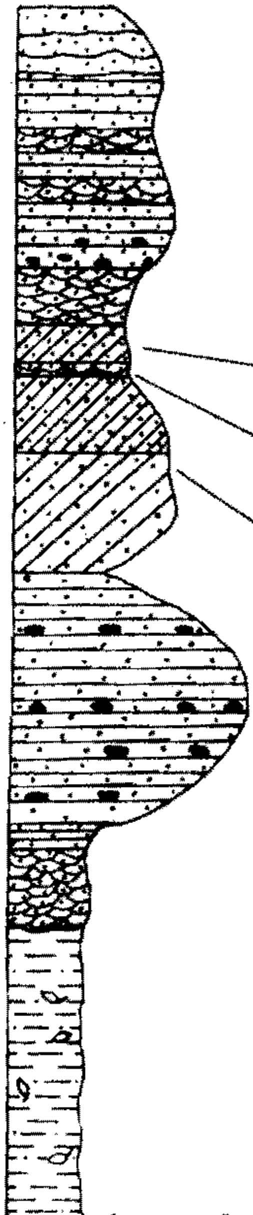
(Base of section)

Bullion Creek Formation

Location: T.129N., R.95W., sec. 25, NE¼, SW¼. Section measured on southeast end of northwest-southeast-trending sandstone ridge, by cattle gate. Location is about 3/8 miles south of Haynes cemetery.

Elevation at top of section: 2690 feet.

Thickness: 8 metres (27 feet).



Calcareous sandstone; very fine to medium; pale yellow to brownish yellow; contains light gray claystone, siltstone clasts (.5-6 cm.) near base; plane-bedded, with some small-scale cross-bedding; upper 0.5 m. is horizontally jointed; 1.75 m.

Calcareous sandstone; very fine to fine; pale yellow to brownish yellow; small-scale cross-bedded; 0.4 m.

Calcareous sandstone; very fine to medium; pale yellow to brownish yellow; large-scale cross-bedded; 0.25 m.

Calcareous sandstone; very fine to fine; pale yellow to brownish yellow; small-scale cross-bedded; 0.1 m.

Calcareous sandstone; concretionary form; very fine to medium; pale yellow to brownish yellow; large-scale cross-bedded; 1.3 m.

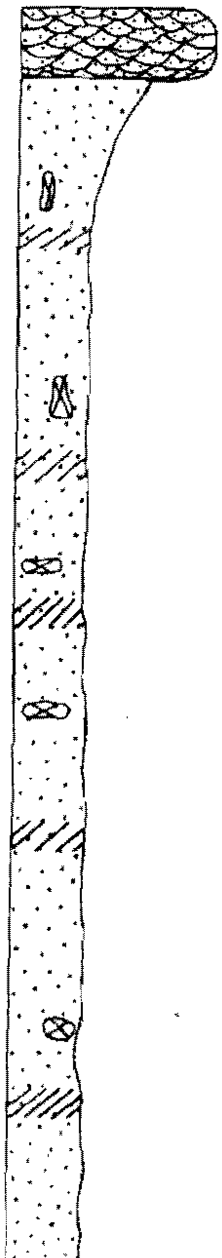
Calcareous sandstone; elongate concretionary form; very fine to fine; pale yellow to brownish yellow; contains light gray claystone, siltstone clasts (.5-2 cm.) on bedding paanes; plane-bedded; 1.7 m.

Sand; very fine to fine; pale yellow; small-scale cross-bedded; upper 0.2 m. is plane-bedded; 0.7 m.

Clay; silty; diffuse color bands of gray and grayish brown; contains plant fragments; 2.0 m.

(Base of section)

Bullion Creek Formation
Location: T.130N., R.95W., sec. 30, SW¼, SW¼. Section measured at roadcut, east side of north-south blacktop road, 3.25 miles north of Hettinger, N.D.
Elevation at top of section: 2870 feet.
Thickness: 19.6 metres (64 feet).



Calcareous sandstone; elongate concretionary form; very fine to medium; pale brown to light gray; small-scale cross-bedded; 0.5 m.

Sand; very fine to medium; light gray; contains large (10-35 cm.), tubular and irregularly shaped iron oxide concretions; massive; large-scale cross-bedded in places; 8.0 m.

(Section continued on next page.)

Sand; very fine to medium; light gray; contains large, tubular and irregularly shaped iron oxide concretions (10-30 cm.); massive; large-scale cross-bedded in places; 3.9 m.

Carbonaceous clay; silty; dark gray to dark brown; 0.7 m.

Clay; silty; iron oxide-stained; 0.25 m.

Concealed; 0.45 m.

Sand; very fine to fine; and silt; slightly clayey; light brown; massive; 0.7 m.

Clay; silty; brownish gray; 0.1 m.

Sand; very fine to fine; and silt; slightly clayey; massive; 0.1 m.

Concealed; 0.4 m.

Sand; very fine to fine; and silt; light gray to light brown; massive; 0.8 m.

Clay; silty; diffuse color bands of light gray to gray and light brown; contains plant fragments in places; thinly laminated in places; 2.0 m.

(Section continued on next page.)

Clay; silty; diffuse color bands of light gray to gray and light brown; contains plant fragments near top; thinly laminated in places; 2.2 m.

(Base of section)

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REFERENCES


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# MAP OF DISTRIBUTION OF ELONGATE SANDSTONE CONCRETIONS, BULLION CREEK AND SLOPE FORMATIONS (PALEOCENE), ADAMS COUNTY, NORTH DAKOTA

PLATE I
Parsons, 1980